# SR 405 Vortechs$^{TM}$ Water Quality Monitoring Project

# Final Report

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for the
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## EXECUTIVE SUMMARY

This report summarizes the methods and results of data collected for the Washington State Department of Transportation (WSDOT) State Route 405 Vortechs™ Water Quality Monitoring Project (SR 405 Project). The purpose of the project was to evaluate (1) the removal efficiency and (2) the maintenance needs of a Vortechs Stormwater Treatment System (model 11000) installed along the northbound lanes of SR 405 in northern King County, Washington.

Taylor Associates, Inc. monitored rainfall and flow and collected water quality samples during 11 storm events from March 2001 to February 2002. Removal efficiencies were calculated for several parameters on a per-storm basis and on an aggregated basis for all storm events combined. In summary, the removal efficiency results indicate:

- For total suspended solids (TSS), the aggregate removal efficiency for all storm events was approximately 20 percent, and the TSS removal efficiencies for each storm event were fairly consistent. Correlation analysis indicated generally positive relationships between (1) storm removal efficiencies and peak flow rate and (2) between storm removal efficiencies and inlet concentrations.

- For turbidity, the aggregate removal efficiency for all storm events was approximately 15 percent. The turbidity removal efficiencies for individual storm events varied moderately.

- For total zinc, the aggregate removal efficiency for all storm events was approximately 2 percent. The total zinc removal efficiencies for individual storm events were fairly consistent.

- For dissolved zinc, the aggregate removal efficiency for all storm events was approximately -35 percent. The dissolved zinc removal efficiencies for individual storm events varied greatly.

- For total phosphorus (TP), the aggregate removal efficiency for the eleven storm events was approximately 15 percent. The TP removal efficiencies for individual storm events varied moderately.

- For orthophosphate phosphorus (ortho-P), the aggregate removal efficiency for all storm events was approximately -35 percent. The ortho-P removal efficiencies for individual storm events varied greatly.

- For all parameters, outlet concentrations showed a moderate to high positive correlation to inlet concentrations.

Based on the TSS removal efficiency results, the Vortechs unit evaluated would be unlikely to meet Washington State Department of Ecology's (Ecology) guidelines for emerging stormwater treatment technologies (Ecology 2001c). Ecology's basic treatment criterion is 80 percent removal of TSS for influent concentrations that are greater than 100 mg/L and less than 200 mg/L. This performance goal assumes the stormwater being treated has a typical particle size distribution of $D_{90}$ of 212 μm, $D_{80}$ of 150 μm, and $D_{50}$ of 75 μm. (Ecology 2001a). Particle sizes measured at the inlet station for this project were consistently smaller than the Ecology's typical stormwater runoff particle sizes. The smaller particle sizes were thought to be one of the possible reasons for the TSS removal efficiencies in the low range of 20 percent.

Visual observations of sediment movement through the Vortechs provided additional information of system performance. Sand and gravel was observed moving through the inlet pipe as bedload into the Vortechs unit. Sediment this coarse was not observed in the outlet pipe and was presumed to be removed by the Vortechs. These observations suggest the net total sediment removal by the Vortechs was greater than the measured TSS removal.

Maintenance needs of the Vortechs unit were determined by maintenance inspections that consisted of measuring sediment depth in the grit chamber of the unit and in manhole sumps immediately upstream and downstream of the unit. In addition, visual inspections were made for sheen and floatables. The results from the maintenance inspections indicated:

- The Vortechs unit monitored for this study is providing coarse solids removal and is extending the maintenance cycle of the downstream wet pond.

- During the two years the Vortechs unit was monitored, sediment accumulation occurred primarily in the upstream manhole until the sump was full. The rate of sediment accumulation in the grit chamber increased once the upstream manhole sump was full.

- The Vortechs unit and adjacent upstream and downstream manholes require sediment removal approximately every two years, perhaps more frequently with normal or greater than normal annual rainfall.

Although the evaluated Vortechs would be unlikely to meet Ecology's basic treatment criterion, it would possibly meet Ecology's criteria for Pretreatment for Treatment Train/Retrofit Applications. While Ecology has no explicit performance standards for these applications, a lesser performance (than required for basic treatment in stand-alone technologies) may be acceptable (Ecology 2001c). Ecology has selected the following guidelines for assessing technologies at less-than-basic treatment levels:

- Provides mostly coarse solids removal and can be specified to improve receiving water aesthetics by removing litter and debris.

- Improves the effectiveness, extends the useful life, or extends the maintenance cycle of a downstream treatment device or infiltration facility.

Data from this study can be combined with data from other similar studies to determine statistically significant results. Other appropriate studies would ideally include those being conducted on Vortechs units under the guidelines from Ecology (2001c) in similar and different installations.

## 1.0 PROJECT DESCRIPTION

This report summarizes the methods and results of data collected for the Washington State Department of Transportation (WSDOT) State Route 405 Vortechs$^{TM}$ Monitoring Project (SR 405 Project). The purpose of the project was to evaluate the removal efficiency and maintenance needs of a Vortechs Stormwater Treatment System installed along the northbound lanes of SR 405 (Figure 1). Taylor Associates, Inc. monitored rainfall and flow and collected water quality samples during 11 storm events from March 2001 to February 2002. This report presents the flow monitoring and stormwater data collected during this period. In this section, the problem definition and motivation for the project is described. In addition, the stormwater treatment technology that was evaluated is described and the project objectives are stated.

### 1.1 PROBLEM DEFINITION

Untreated stormwater runoff from roadways often contributes to water quality degradation (Burton and Pitt 2002). Potential pollutants from roadway runoff may include high concentrations of suspended solids, nutrients, and metals. In addition, litter, oil, and grease are frequently present in roadway runoff. WSDOT oversees miles of roadways within Washington State and is addressing the treatment of stormwater from its highways. As technologies to treat stormwater emerge and are refined, WSDOT is collecting data on the performance and maintenance requirements of these units to identify appropriate technologies applicable to treating stormwater runoff from its roadways.

Stormwater from roadways is treated (if at all) by the use of public-domain technologies such as vegetated swales and retention/detention ponds. The removal efficiencies of potential pollutants by these treatment systems vary with several factors including inflow concentrations, maintenance activity, and the size of the system. In addition, these treatment systems require a land often in areas where land is sparse and prices are at a premium. Newer structural technologies such as the Vortechs unit are located below ground and can be sited within state right-of-ways minimizing land acquisition costs. In addition, maintenance of these emerging technologies may be more cost-effective than for swales and ponds. These emerging technologies are also designed to maximize removal and minimize resuspension of trapped solids. Compared to more traditional public domain technologies, little data exists on the removal efficiencies and maintenance needs associated with the use of these emerging technologies in the field.

### 1.2 STORMWATER TREATMENT TECHNOLOGY DESCRIPTION

The Vortechs unit (manufactured by Vortechnics$^{TM}$) is intended for use as a water quality protection device for stormwater runoff from new developments and retrofit applications including parking lots, roadways, watershed protection, and industrial facilities. The Vortechs unit is a below-grade structure constructed of precast concrete and aluminum. The unit is designed to remove sediment and petroleum-based liquids from stormwater runoff and to prevent

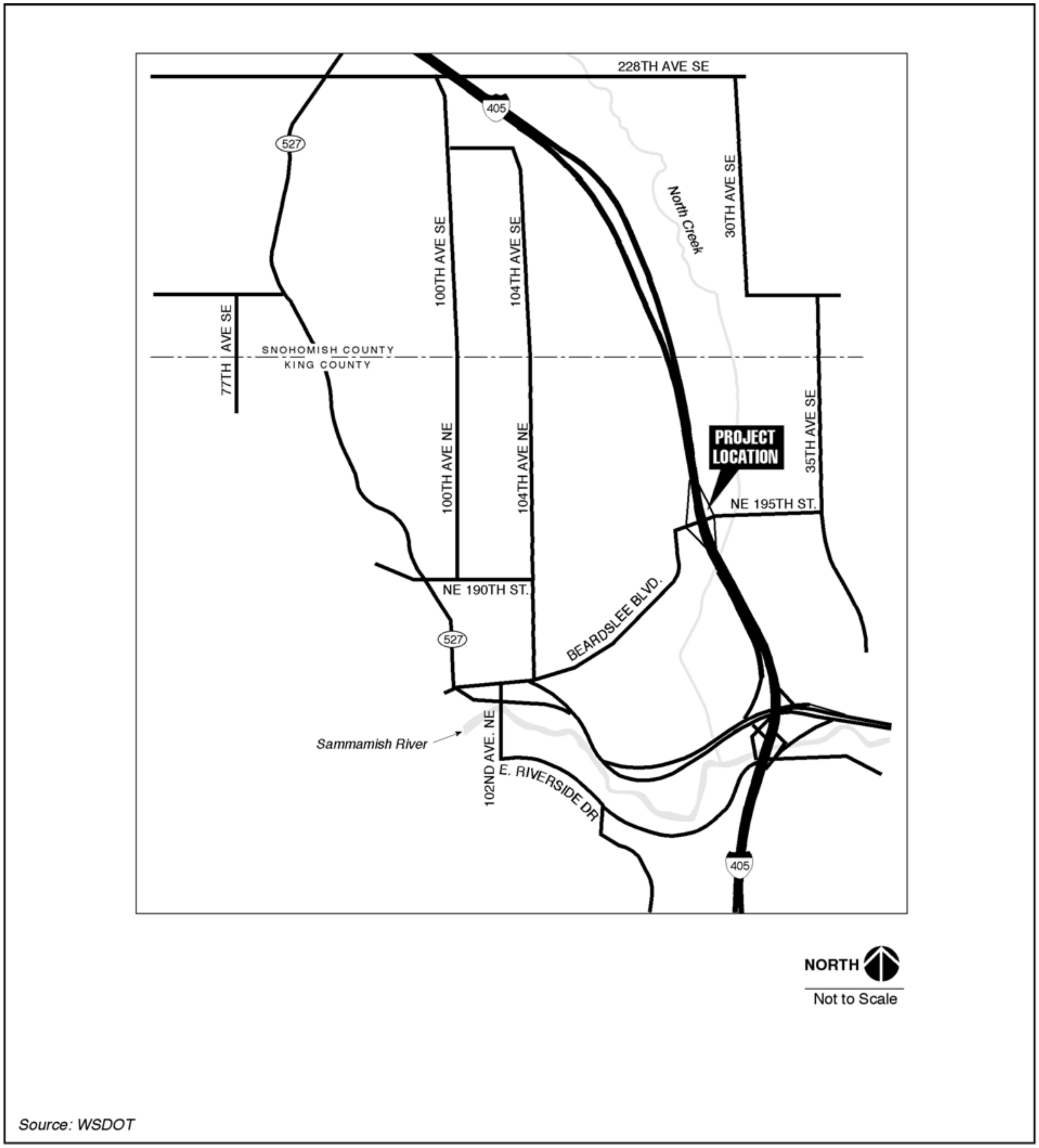


Figure 1. Project Location

the reentrainment of these pollutants once settled in the unit. The Vortechs unit consists of three chambers (Figure 2): the grit chamber, oil chamber/baffle wall, and a flow control chamber. Stormwater enters the grit chamber through a tangential inlet and the swirling motion directs settleable solids toward the center of the chamber. Sediment is caught in the swirling flow path and settles in a pile within the grit chamber after the storm event is over. A baffle wall traps

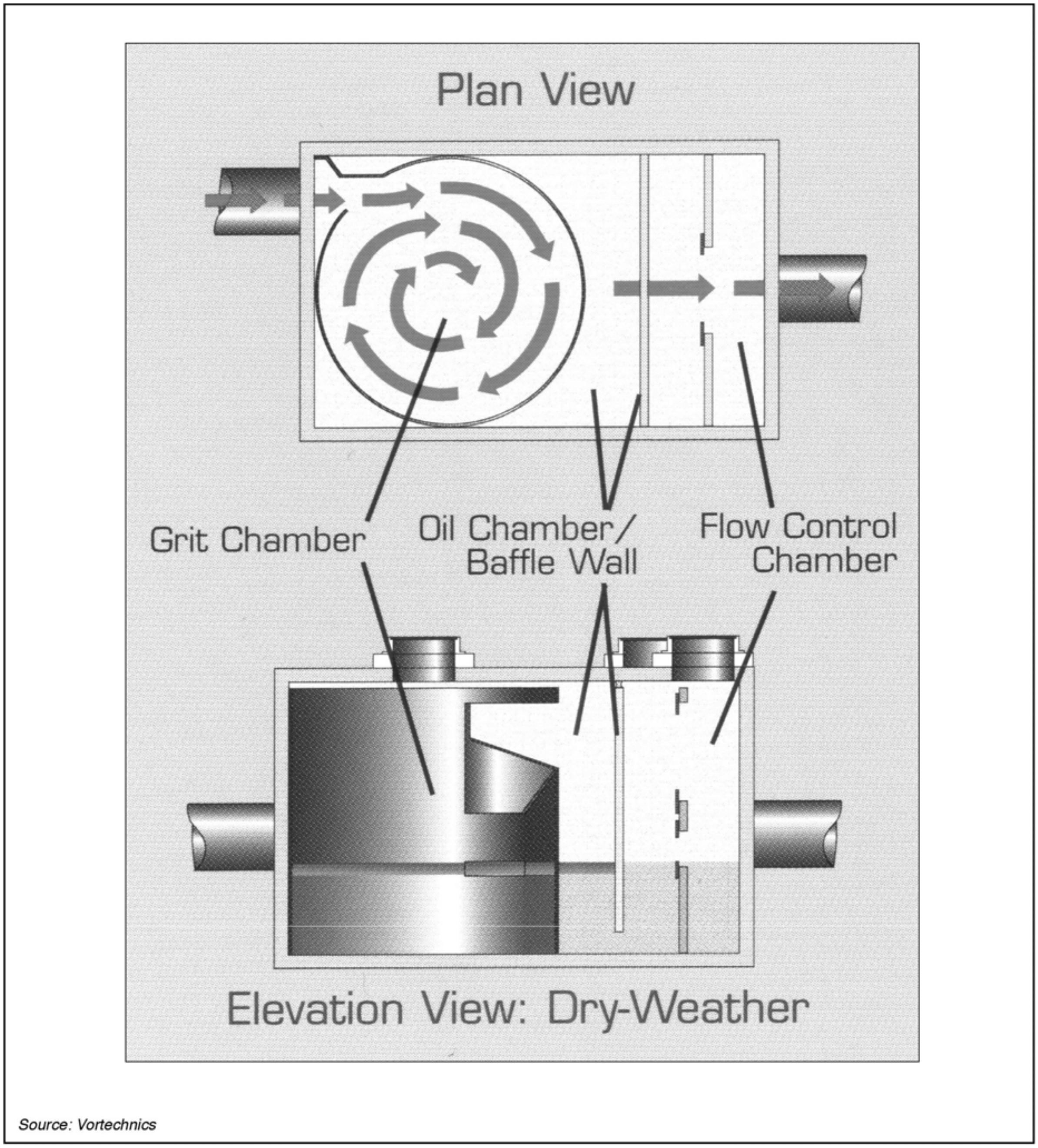


Figure 2. Vortechs Stormwater Treatment System

floatables in the oil chamber. As flow increases to the unit, the flow control chamber causes the inlet pipe to become submerged and keeps captured pollutants inside the grit chamber by reducing forces that encourage resuspension and washout. Maintenance consists of periodic removal of accumulated sediments and floatables from the unit by a vacuum truck. Further information on the Vortechs unit can be found on the web site: http://www.vortechnics.com.

The Vortechs unit evaluated for this project is a Model 11000, the second largest model produced by Vortechnics. It has a 10-foot diameter grit chamber, 5.5 cubic yards of sediment storage capacity, 1800 gallons of oil storage capacity, and is designed to treat flows up to 17.5 cfs (peak design flow). Pre-construction calculations made by WSDOT indicate the unit for this project treats flows from a 28-acre drainage area of which 66 percent is impervious, although these watershed characteristics have not been verified. The design storms for this unit were modeled by WSDOT based on the Soil Conservation Service (SCS) hydrograph method; the modeled flow rates are presented in Table 1.

Table 1. Design Storms (SCS Hydrograph Method)

| Storm Return Period (24-hour) | Modeled Flow Rate (cfs) |
| --- | --- |
| 6-month | 4.0 |
| 2-year | 7.2 |
| 10-year | 11.4 |
| 100-year | 18.1 |

### 1.3 Project Objectives

The objectives of the SR 405 Project, as outlined in the Quality Assurance Project Plan (QAPP, Taylor Associates, Inc. 2001), are:

1. Evaluate the removal efficiency of the Vortechs unit by monitoring flow and rainfall and collecting flow-weighted composite samples upstream and downstream of the unit for 12 storm events.

2. Evaluate the maintenance needs of the Vortechs unit by monitoring sediment depth and presence of visible sheen in the Vortechs unit and in the manholes immediately upstream and downstream of the unit on a monthly basis.

The frequency of maintenance inspections performed for the second objective changed from monthly to quarterly in July 2001. The data showed the rate of sediment accumulation to be slow enough to warrant inspections only as frequently as once per quarter.

## 2.0 METHODS

The methods for sample collection, sample processing, and data analysis are described in detail in the QAPP (Taylor Associates 2001). The methods were based on the draft Technology Assessment Protocol – Ecology (TAPE, Ecology 2001a), which is Washington State Department of Ecology's (Ecology) guideline for monitoring stormwater treatment technologies. Since the SR 405 Project began, the TAPE guideline has been updated; the methods for this project were based on the draft TAPE version at the time the QAPP was prepared. The experimental design for data collection and the methods for data analysis from the QAPP are presented below. For the full description of the data collection methods used for this project refer to the QAPP.

## 2.1 DATA COLLECTION

The first objective of the project is to evaluate the removal efficiency of a suite of water quality parameters by the Vortechs unit. The data for evaluating removal efficiencies was based on water samples and flow and rainfall data collected during storm events. Figure 3 shows a schematic of the monitoring equipment layout and setup at the site. Flow-weighted composite samples were collected upstream and downstream of the Vortechs unit using ISCO 6700C automated samplers. The upstream sampler was equipped with an ISCO 730 module to measure water level in the inlet pipe of the Vortechs unit, and the downstream sampler was equipped with an ISCO 750 module to measure water level and water velocity using an area-velocity sensor situated in the outlet pipe. Water level and velocity was collected in 5-minute intervals. Data from the area-velocity sensor in the outlet pipe was used to calculate flow and flow-pace the sample collection for both the upstream and downstream samplers. Flow rate (in the outlet pipe) was calculated using an area-velocity equation based on water depth, cross-sectional area of the pipe, and water velocity.

Each sampler was equipped with a 10 L polyethylene sample bottle, into which 200 mL aliquots were pumped per designated flow volume passing through the Vortechs unit. A maximum of 50 aliquots could be collected in each bottle. This method provided 2 flow-weighted composite samples for each storm event sampled: one collected immediately upstream of the Vortechs unit and one collected immediately downstream.

The sampling program was initiated by a rise in water level (enable level) of approximately 0.1 feet above the pre-storm water level as measured by the area-velocity sensor in the outlet pipe. After several storm events were captured, a pattern was noticed of aliquots sometimes being missed at the inlet during the beginning and end of storm events. This problem was solved by increasing the enable level to 0.3 feet above pre-storm water levels to ensure that the sampler intake line at the inlet was completely submerged throughout the entire sampling program.

Rainfall was collected on-site using an ISCO 674 tipping bucket rain gauge. Rainfall was recorded in 0.01-inch increments.

The QAPP indicated that 12 storm events would be sampled. Fourteen storm events were targeted during the project schedule, of which 11 produced acceptable data and samples. At project end, WSDOT decided not to extend the project to collect samples from a 12th storm event. A storm event for this project was defined as having a minimum runoff duration of 1 hour, minimum rainfall depth of 0.25 inches, and 6 hours of no rainfall before and after the storm event. These storm event criteria were based on recommendations in the draft TAPE methodology (Ecology 2001a). Based on best professional judgment, five samples were submitted for analysis that deviated slightly from the storm event criteria (see Table 5).

Rainfall, sample collection times, water level, water velocity, and flow data were stored in an ISCO® Flowlink database. Lab results were stored in a Microsoft® Excel database. Storm event graphs were produced for each storm event (Appendix A) and show rainfall, inlet and outlet water level, sample event marks, and outlet water velocity and flow rate.

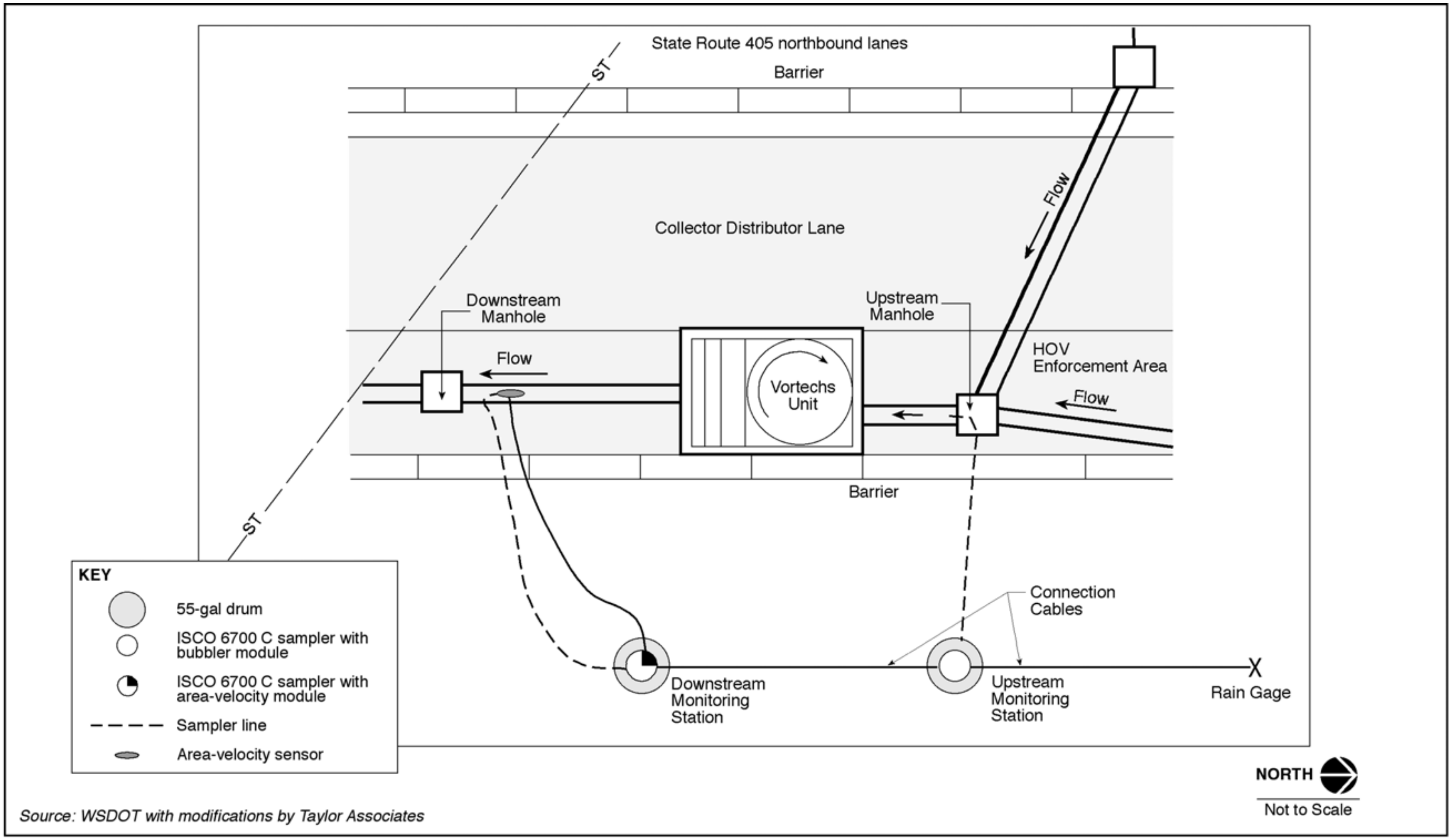


Figure 3. Monitoring Equipment Schematic

Once samples were collected from the field site, they were taken to North Creek Analytical (NCA) laboratory where 1.5 to 4 liters of subsample were removed by shaking and pouring from each composite sample. Laboratory analysis was done on the subsamples for the water quality parameters presented in Table 2. The full laboratory reports from NCA are presented in Appendix A.

Table 2. Water Quality Parameters

| Parameter | Method | Preservation Method | Holding Time | Laboratory |
|---|---|---|---|---|
| Total Suspended Solids (TSS) | EPA 160.2 | cool, 4C | 7 days | NCA[1] |
| Turbidity | EPA 180.1 | cool, 4C | 48 hours | NCA |
| Hardness | SM 2340B | $HNO_3$ to pH<2 | 6 months | NCA |
| Total Zinc | EPA 200.8 | $HNO_3$ to pH<2, cool, 4C | 6 months | NCA |
| Dissolved Zinc | EPA 200.8 | Filter, $HNO_3$ to pH<2, cool, 4C | 24 hrs until preserved, 6 months | NCA |
| Total Phosphorus (TP) | EPA 365.2 | $H_2SO_4$ | 28 days | NCA |
| Orthophosphate phosphorus (Ortho-P) | EPA 365.2 | Filter | 48 hours | NCA |
| pH | EPA 150.1 | Cool, 4C | 24 hours | NCA |
| Particle Size Analysis (PSA) | Laser backscatter | Cool, 4C | 48 hours | UW[2] |

1 NCA – North Creek Analytical Laboratory
2 UW – University of Washington

Particle size analysis (PSA) was determined by the University of Washington (UW) Department of Civil Engineering on up to 1 liter of subsample that was collected by shaking and pouring from the composite. The UW used the Sequoia Scientific LISST-Portable particle analyzer for the PSA analysis, which measures the scattering of small-angle laser beams from particles in solution to determine particle sizes between 1.25 to 212 micrometers. Particles larger than 212 micrometers were sieved out prior to the analysis. Appendix A contains the results and methods of the PSAs as provided by the UW.

Quality assurance/quality control (QA/QC) samples were collected for 5-10 percent of the total storm events that were sampled. QA/QC samples included 1 field blank and 2 field splits. The field blank was collected by pumping deionized (DI) water through the outlet sample line after storm #3. The field split was a subsample taken by shaking and pouring from the composite samples from each station for storm #9.

The second objective of the project is to evaluate the maintenance requirements of the Vortechs unit. Data for maintenance requirements was collected during maintenance inspection field visits. These visits occurred approximately monthly from March 2000 to June 2001 and then approximately quarterly from July 2001 to February 2002. Data collected during the maintenance inspections consisted of sediment depths measured at three locations: the grit chamber of the Vortechs unit; the manhole sump immediately upstream of the unit; and the manhole sump immediately downstream of the unit (see Figure 3).

Initially, sediment depth was measured from the surface using a collapsible pole to measure the difference between the sediment surface and chamber floor. As the sediment accumulated, this method became inaccurate since the pole would become separated when it was pulled up. Subsequently, sediment depth was determined by measuring down with a tape measure from the manhole rim above each chamber to the sediment surface. This value was subtracted from the distance from the manhole rim to the chamber floor, thereby giving a sediment depth. In addition, qualitative notes were made of visible sheen and floating objects in each of the three chambers.

## 2.2 Data Analysis

The scope of work for the SR 405 Project included analysis of three types of removal efficiencies. The equations used to calculate removal efficiencies were taken from the draft TAPE guidelines (Ecology 2001a) and are shown below. Removal efficiencies were calculated for TSS, turbidity, total zinc, dissolved zinc, TP, and ortho-P. The goal of the removal efficiency analysis is to provide initial information and contribute to a larger set of data on removal efficiencies of technologies such as the Vortechs unit. Providing statistically significant results at a given confidence level is not the goal of this project, therefore, no statistical tests were performed. As outlined in the QAPP the statistical analysis was limited to calculating correlation coefficients (r-values) on scatter plots of removal efficiencies (see section 4.1).

### 2.2.1 Removal Efficiency Method 1

The first method for calculating removal efficiency is referred to as the Storm Removal Efficiency (SRE). The SRE can be used to calculate removal efficiencies associated with each water quality parameter for an individual storm event.

$$SRE_n = 100 * (X_{in,n} - X_{out,n}) / X_{in,n}$$

n = storm event number
$X_{in,\,n}$ = flow-weighted inlet concentration of parameter for storm event n
$X_{out,n}$ = flow-weighted outlet concentration of parameter for storm event n

### 2.2.2 Removal Efficiency Method 2

The second method of calculating removal efficiency combines results for the 11 storm events and is called the Aggregate Removal Efficiency (ARE). The ARE Method uses total storm volumes (Method 2a : $ARE_{tsv}$) and the arithmetic mean of storm flow rates (Method 2b : $ARE_{mfr}$). Methods 2a and 2b each provide single values of removal efficiency for each water quality parameter. Mean flow rate was calculated as the total storm event flow volume divided by the total storm event time.

Method 2a: $ARE_{tsv} = 100 * (A - B) / A$

$A = (X_{in,1}*V_1) + (X_{in,2}*V_2) +\ldots+(X_{in,n}*V_n)$
$B = (X_{out,1}*V_1) + (X_{out,2}*V_2) +\ldots+(X_{out,n}*V_n)$
$V_n$ = total volume of storm event n

Method 2b: $ARE_{mfr} = 100 * (C - D) / C$

$C = (X_{in,1}*Q_1) + (X_{in,2}*Q_2) +\ldots+(X_{in,n}+Q_n)$
$D = (X_{out,1}*Q_1) + (X_{out,2}*Q_2) +\ldots+(X_{out,n}+Q_n)$
$Q_n$ = mean flow rate during storm event n

### 2.2.3 Removal Efficiency Method 3

The third method for calculating removal efficiency combines the results for the 11 storm events and is called the Aggregate Removal Efficiency Geometric Mean (AREG). The AREG uses the geometric mean of event mean concentrations (EMC) multiplied by the total flow volume for all storms (Method 3a: $AREG_{tsv}$) or multiplied by the mean flow rate for all storm events (Method 3b: $AREG_{mfr}$).

Method 3a: $AREG_{tsv} = 100 * (E - F) / E$

$E = ((X_{in,1} * X_{in,2} * \ldots * X_{in,n})^{1/n}) * V_{tot}$
$F = ((X_{out,1} * X_{out,2} * \ldots * X_{out,n})^{1/n}) * V_{tot}$
$V_{tot}$ = total volume of all storm events = $V_1 + V_2 + \ldots V_n$

Method 3b: $AREG_{mfr} = 100 * (G - H) / G$

$G = ((X_{in,1} * X_{in,2} * \ldots * X_{in,n})^{1/n}) * Q_{ave}$
$H = ((X_{out,1} * X_{out,2} * \ldots * X_{out,n})^{1/n}) * Q_{ave}$
$Q_{ave}$ = mean flow rate for all storm events $= (Q_1*T_1 + Q_2*T_2 +\ldots+ Q_n*T_n)/T_{tot}$
$T_n$ = duration of storm event n
$T_{tot}$ = total duration of all storm events = $T_1 + T_2 + \ldots + T_n$

For this project, Method 3a produces the same values as Method 3b since $V_{tot}$ and $Q_{ave}$ drop out of the AREG equations. Therefore, a single AREG value is reported for each parameter for Method 3.

## 3.0 RESULTS

Results are presented in this section for storm event characteristics, water quality data, removal efficiencies, particle size analysis, field QA/QC activities, and maintenance inspections. Appendix A contains additional result information including storm event graphs, laboratory reports, and completed field sheets for each of the 11 storm events with samples, rainfall, and runoff characteristics that meet the criteria per the QAPP.

### 3.1 STORM EVENTS

The QAPP called for 12 storm events to be monitored for sample collection over the 12-month project period (March 2001 through February 2002). Fourteen storm events in total were targeted for sample collection, 11 of which were successfully sampled and 3 of which were unsuccessfully sampled due to equipment error or failure to meet storm event and sample collection criteria per the project QAPP.

Table 3 summarizes characteristics of each successfully sampled storm event. Storm event rainfall depth ranged from 0.21 to 1.73 inches and peak 1-hour rainfall intensity ranged from 0.09 to 0.44 inches per hour. The antecedent dry period prior to each storm event ranged from 7 to 603 hours. Since the on-site rain gauge collected rainfall data only during storm events, antecedent dry periods were determined from rainfall data publicly accessible through the UW Department of Atmospheric Sciences via the website http://www.atmos.washington.edu/.

Storm event durations ranged from 4 to 38 hours, which was calculated from the time that water level rose above pre-storm depth to the time when level returned to pre-storm depth after the last sample was taken. The peak flow rate during storm events ranged from 0.7 to 10.7 cubic feet per second (cfs) and was determined from the highest single datum (5-minute interval).

During storm #1, subsamples 3, 4, 5, 26, and 27 (out of 27 total) had a “no liquid detected” (NLD) message for the inlet sample. An NLD message usually indicates that the sample intake line was not fully submerged and a mixture of air and water was being pumped, which prevents the full aliquot volume of 200 mL to be collected. For storm #5, subsamples 1 and 2 (out of 21) at the inlet had an NLD message. For storm #7, subsample 14 (out of 15) at the inlet had an NLD message. After storm #7, the NLD problem was solved by slightly increasing the enable level at which the sampling program was initiated.

Table 3. Storm Event Characteristics

| Storm No. | Date | Total Rainfall (in) | Storm Duration [1] (hrs) | Antecedent Dry Period [2] (hrs) | Total Flow Volume (cf) | Flow Volume per 0.01" Rain (cf/0.01 in) | No. samples in composite inlet | No. samples in composite outlet | Peak Rainfall Intensity [3] (in/hr) | Peak Flow Rate (cfs) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3/25/01 | 0.52 | 13 | 142 | 15090 | 290 | 22 of 27 | 27 of 27 | 0.27 | 2.5 |
| 2 | 4/17/01 | 0.21 | 4 | 75 | 6284 | 299 | 13 of 13 | 13 of 13 | 0.14 | 1.0 |
| 3 | 5/15/01 | 0.50 | 22 | 30 | 13717 | 274 | 21 of 21 | 21 of 21 | 0.09 | 0.7 |
| 4 | 8/22/01 | 1.73 | 38 | 603 | 65531 | 379 | 50 of 50 | 50 of 50 | 0.44 | 6.5 |
| 5 | 10/11/01 | 0.40 | 19 | 24 | 25613 | 640 | 18 of 20 | 20 of 20 | 0.32 | 10.7 |
| 6 | 11/28/01 | 0.94 | 15 | 60 | 37369 | 398 | 50 of 50 | 50 of 50 | 0.2 | 2.4 |
| 7 | 1/2/02 | 0.44 | 25 | 31 | 13210 | 300 | 13 of 15 | 15 of 15 | 0.1 | 1.1 |
| 8 | 1/7/02 | 1.00 | 26 | 7 | 40040 | 400 | 50 of 50 | 50 of 50 | 0.13 | 2.0 |
| 9 | 1/25/02 | 0.94 | 15 | 96 | 35554 | 378 | 50 of 50 | 50 of 50 | 0.2 | 3.5 |
| 10 | 2/11/02 | 0.36 | 13 | 62 | 10234 | 284 | 22 of 22 | 22 of 22 | 0.15 | 1.3 |
| 11 | 2/22/02 | 1.56 | 33 | 38 | 60882 | 390 | 50 of 50 | 50 of 50 | 0.13 | 1.8 |

[1] Storm duration refers to the duration for which flow levels were elevated above base flow.
[2] Antecedent dry period was determined from rainfall data publicly accessible through the UW Department of Atmospheric Sciences.
[3] The peak rainfall intensity is the highest rainfall intensity during a one-hour period. This peak is not equivalent to the greatest values shown in the storm event graphs in Appendix A, which are shown for 15-minute intervals (for example 12:00 to 12:15).

Table 4 presents the conformance of each storm event with the criteria outlined in the QAPP. Storm event #s 3, 4, 6, 8, 9, and 10 met all of the storm event criteria. Storm #s 1 and 5 had periods 6 hours or longer without rainfall during the sampling program. Samples from storm #1 were accepted since the period without rainfall was exactly 6 hours (and not longer) and all other sample and storm event criteria were met. Samples from storm #5 were accepted since only a small proportion of subsamples (3 out of 20) had been collected prior to the mid-storm event 8.75-hour dry period and since all other criteria were met. Storm #2 had 0.04 inches less rain than the criteria of 0.25 inches, however the samples were accepted because the minimum rainfall depth criteria in the most recent version of the TAPE guidelines had been lowered to 0.20 inches. The sampling program for storm #7 began after the first 0.15 inches of rain (out of 0.44 inches total) occurred; samples from storm #7 were accepted since all other criteria were met. The samples from storm #11 captured less than 75 percent of the flow volume, however it was decided to submit the samples since only the tail end of the storm was not sampled.

Table 4. Storm Event and Sample Event Conformance with QAPP Criteria

| Storm Number | Rainfall ≥0.25"? | 6-hour antecedent dry period? | Runoff duration ≥1 hour? | ≥75% of storm flow volume captured? | Notes |
|---|---|---|---|---|---|
| 1 | Y | N | Y | Y | A 7-hour period of without rain occurred between samples 3 and 5. |
| 2 | N | Y | Y | Y | Rainfall = 0.21" |
| 3 | Y | Y | Y | Y | |
| 4 | Y | Y | Y | Y | |
| 5 | Y | N | Y | Y | A 9-hour period without rain occurred between samples 2 and 4. |
| 6 | Y | Y | Y | Y | |
| 7 | Y | N | Y | Y | Sampler program began after 0.15" (out of 0.44" total) of rain occurred. Program still captured 78% of storm event flow volume. |
| 8 | Y | Y | Y | Y | |
| 9 | Y | Y | Y | Y | |
| 10 | Y | Y | Y | Y | |
| 11 | Y | Y | Y | N | Tail end of storm was not captured because bottles had filled after 64% of storm event flow volume passed. |

## 3.2 WATER QUALITY DATA AND REMOVAL EFFICIENCIES

The results of the laboratory analysis for each inlet and outlet sample and the difference between the inlet and outlet concentrations for each storm event for each parameter are presented in Table 5. Samples for which the parameter was at or below the detection limit are indicated as a non-detect (ND). Differences for ND samples are in *italics* and were calculated using the detection

Table 5. Inlet and Outlet Event Mean Concentration Data

| **Parameter (units) Det. limit range** | **Station** | **Storm #1** | **Storm #2** | **Storm #3** | **Storm #4** | **Storm #5** | **Storm #6** | **Storm #7** | **Storm #8** | **Storm #9** | **Storm #10** | **Storm #11** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TSS (mg/L) 4.0 | inlet | 200 | 140 | 55.0 | 430 | 580 | 30.0 | 230 | 80.0 | 190 | 110 | 53.0 |
| | outlet | 180 | 120 | 44.0 | 310 | 440 | 24.0 | 140 | 63.0 | 150 | 130 | 73.0 |
| | difference | 20 | 20 | 11 | 120 | 140 | 6 | 90 | 17 | 40 | -20 | -20 |
| Turbidity (NTU) 1.0-10.0 | inlet | 152 | 78.6 | 37.6 | 187 | 280 | 23.7 | 7.3 | 32.4 | 53.9 | 39.4 | 36.5 |
| | outlet | 129 | 77.6 | 57.6 | 174 | 150 | 17.4 | 7.2 | 31.3 | 56.0 | 48.0 | 38.2 |
| | difference | 23 | 1 | -20 | 13 | 130 | 6.3 | 0.1 | 1.1 | -2.1 | -8.6 | -1.7 |
| pH (unitless) | inlet | 6.78 | 6.47 | 7.01 | 6.8 | 7 | 6.92 | 7.27 | 7.02 | 6.89 | 7.06 | 6.99 |
| | outlet | 6.96 | 6.56 | 6.86 | 6.87 | 6.75 | 7 | 7.16 | 7.12 | 6.99 | 7.02 | 6.98 |
| | difference | -0.18 | -0.09 | 0.15 | -0.07 | 0.25 | -0.08 | 0.11 | -0.1 | -0.1 | 0.04 | 0.01 |
| Hardness (mg eq. CaCO3/L) 1.00-2.00 | inlet | 38.3 | 32.3 | 27.3 | 50.5 | 64.3 | 17.0 | 38.6 | 28.7 | 31.1 | 27.2 | 26.5 |
| | outlet | 40.4 | 36.2 | 27.9 | 51.7 | 52.2 | 16.7 | 36.8 | 29.1 | 26.0 | 29.1 | 26.6 |
| | difference | -2.1 | -3.9 | -0.6 | -1.2 | 12.1 | 0.3 | 1.8 | -0.4 | 5.1 | -1.9 | -0.1 |
| Total Zinc (mg/L) 0.0100 | inlet | 0.1290 | 0.1120 | 0.0812 | 0.1490 | 0.1350 | 0.0153 | 0.1410 | 0.0684 | 0.0972 | 0.1110 | 0.0617 |
| | outlet | 0.1170 | 0.0921 | 0.0733 | 0.1500 | 0.1360 | 0.0425 | 0.1180 | 0.0636 | 0.0766 | 0.1220 | 0.0766 |
| | difference | 0.012 | 0.0199 | 0.0079 | -0.001 | -0.001 | -0.0272 | 0.023 | 0.0048 | 0.0206 | -0.011 | -0.0149 |
| Diss. Zinc (mg/L) 0.0100 | inlet | 0.0316 | 0.0374 | 0.0397 | 0.0190 | ND[1] | 0.0117 | 0.0285 | 0.0183 | 0.0156 | 0.0183 | 0.0314 |
| | outlet | 0.0271 | 0.0316 | 0.0400 | 0.0171 | 0.0140 | 0.0383 | 0.0228 | 0.0134 | 0.0144 | 0.0210 | 0.0766 |
| | difference | 0.0045 | 0.0058 | -0.0003 | 0.0019 | *-0.004*[2] | -0.0266 | 0.0057 | 0.0049 | 0.0012 | -0.0027 | -0.0452 |
| TP (mg/L) 0.00500-0.0250 | inlet | 0.5100 | 0.2210 | 0.07420 | 0.2530 | 0.9220 | 0.04040 | 0.4610 | 0.54000 | 0.06980 | 0.21400 | 0.08600 |
| | outlet | 0.4430 | 0.28600 | 0.08920 | 0.2530 | 0.7640 | 0.04500 | 0.26800 | 0.1840 | 0.18000 | 0.25700 | 0.09420 |
| | difference | 0.067 | -0.065 | -0.015 | 0 | 0.158 | -0.0046 | 0.193 | 0.356 | -0.1102 | -0.043 | -0.0082 |
| Ortho-P (mg/L) 0.00200 | inlet | ND[1] | 0.00375 | 0.00375 | 0.0421 | 0.0264 | 0.012 | 0.00339 | 0.0275 | 0.0138 | 0.0171 | 0.00457 |
| | outlet | 0.00259 | 0.00322 | 0.00349 | 0.0376 | 0.0109 | 0.011 | ND[1] | 0.0064 | 0.0112 | 0.00773 | 0.00271 |
| | difference | *-0.00059*[2] | 0.00053 | 0.00026 | 0.0045 | 0.0155 | 0.001 | *0.00139*[2] | 0.0211 | 0.0026 | 0.00937 | 0.00186 |

[1] ND = Non-detect. Result below detection limit.

[2] *Italics* indicate difference calculated using the detection limit for a result that was a ND. Dissolved zinc detection limit was 0.0100 mg/L and ortho-P detection limit was 0.00200 mg/L.

limit for a result that was a ND. The samples collected were flow-weighted composites, therefore the inlet and outlet concentrations in Table 5 are event mean concentrations (EMCs). Laboratory detection limits were consistent for some parameters (TSS, total zinc, dissolved zinc, and ortho-P) and varied for others (turbidity, hardness, and TP) from storm to storm. Laboratory results in Table 5 are presented using significant digits based on the detection limit in the laboratory report.

For TSS, concentrations ranged from 30 to 580 mg/L at the inlet and 24 to 440 mg/L at the outlet. Turbidities ranged from 7.3 to 285 NTU at the inlet and 7.2 to 174 NTU at the outlet. pH values ranged from 6.47 to 7.27 at the inlet and 6.56 to 7.16 at the outlet. Hardness concentrations ranged from 17.0 to 64.3 mg equivalent of $CaCO_3$/L at the inlet and 16.7 to 52.2 mg/L equivalent of $CaCO_3$/L at the outlet. Total zinc concentrations ranged from 0.0153 to 0.1490 mg/L at the inlet and 0.0425 to 0.1500 mg/L at the outlet. Dissolved zinc concentrations ranged from below the detection limit of 0.0100 to 0.0397 mg/L at the inlet and 0.0134 to 0.0766 mg/L. TP concentrations ranged from 0.04040 to 0.9220 mg/L at the inlet and 0.04500 to 0.4430 mg/L at the outlet. Ortho-P concentrations ranged from below the detection limit of 0.00200 to 0.04210 mg/L at the inlet and below the detection limit of 0.00200 to 0.03760 mg/L at the outlet.

Removal efficiencies were calculated as described above in Section 2.2 for all parameters except pH and hardness. Table 6 presents the results of individual storm event removal efficiencies (SREs) using Method 1. Negative (-) values indicate that the outlet concentration was greater than the inlet concentration. SREs range from -38 percent to 39 percent for TSS, -53 percent to 46 percent for turbidity, -178 percent to 21 percent for total zinc, -227 percent to 27 percent for dissolved zinc, -158 percent to 42 percent for TP, and -30 percent to 77 percent for ortho-P.

Table 6. Storm Removal Efficiencies (Method 1)

| **Storm No.** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| TSS | 10% | 14% | 20% | 28% | 24% | 20% | 39% | 21% | 21% | -18% | -38% |
| Turbidity | 15% | 1% | -53% | 7% | 46% | 27% | 2% | 3% | -4% | -22% | -5% |
| Total Zinc | 9% | 18% | 10% | -1% | -1% | -178% | 16% | 7% | 21% | -10% | -24% |
| Diss. Zinc | 14% | 16% | -1% | 10% | *-40%*[1] | -227% | 20% | 27% | 8% | -15% | -144% |
| TP | 13% | -29% | -20% | 0% | 17% | -11% | 42% | 66% | -158% | -20% | -10% |
| Ortho-P (mg/L) | *-30%*[1] | 14% | 7% | 11% | 59% | 8% | *41%*[1] | 77% | 19% | 55% | 41% |

[1]*Italics* indicate the SRE was calculated using the detection limit for a result that was a ND. Dissolved zinc detection limit was 0.0100 mg/L and ortho-P detection limit was 0.00200 mg/L.

Aggregate removal efficiencies calculated using Methods 2 and 3 are presented in Table 7. Method 2a uses storm event flow volumes, Method 2b uses storm event mean flow rates, and Method 3 uses the geometric mean of the concentration. Aggregate removal efficiencies ranged from 20 percent to 21 percent for TSS, 14 percent to 16 percent for turbidity, -1.6 percent to 3 percent for total zinc, -54 percent to –21 percent for dissolved zinc, 12 percent to 18 percent for total phosphorus, and 31 percent to 37 percent for ortho-P. Negative values indicate that outlet samples had higher concentration than the inlet sample for one or more storm events.

Table 7. Aggregate Removal Efficiencies (Methods 2 and 3)

| Parameter | Method 2a $ARE_{tsv}$[1] | Method 2b $ARE_{mfr}$[2] | Method 3 AREG[3] |
|---|---|---|---|
| TSS | 21% | 20% | 20% |
| Turbidity | 14% | 16% | 15% |
| Total Zinc | -1.6% | 0.8% | 3.0% |
| Diss. Zinc [4] | *-54%* | *-42%* | *-21%* |
| TP | 18% | 12% | 16% |
| Ortho-P [4] | *31%* | *34%* | *37%* |

[1] $ARE_{tsv}$ = Aggregate Removal Efficiency using total storm volumes.
[2] $ARE_{mfr}$ = Aggregate Removal Efficiency using mean flow rates.
[3] AREG = Aggregate Removal Efficiency using geometric mean of concentrations.
[4] *Italics* indicate ARE and AREG values were calculated using the detection limit for a result that was a ND. Dissolved zinc detection limit was 0.0100 mg/L and ortho-P detection limit was 0.00200 mg/L.

### 3.3 PARTICLE SIZE ANALYSIS

Particle size analysis (PSA) was described as a "non-critical" measurement for this project to be done if possible based on constraints of sample volume and availability of UW. Samples from all 11 successfully monitored storm events were submitted and analyzed for PSA. As a non critical measurement, PSA was not included in the objectives of the project and analysis and discussion of the PSA data was not included in the scope of work. Therefore, discussion of the PSA data is minimal.

The results of the particle size analyses for each inlet and outlet sample are presented in Table 8. Values in Table 8 are the particle diameters in micrometers (μm) for the 10th, 20th, 50th, 80th, and 90th percentiles of the logarithmic cumulative distribution. Particle sizes in the 10th percentile ranged from 2.2 to 19.2 μm in the inlet and 2.6 to 19.2 μm in the outlet. Particle sizes in the 20th percentile ranged from 7.1 to 37.2 μm in the inlet and 8.4 to 37.2 μm in the outlet. Particle sizes in the 50th percentile ranged from 22.7 to 85.2 μm in the inlet and 26.7 to 85.2 μm in the outlet. Particle sizes in the 80th percentile ranged from 72.2 to 165 μm in the inlet and outlet. Particle sizes in the 90th percentile ranged from 140 to 195 μm in the inlet and 119 to 195 μm in the outlet. Appendix A contains the reports from the UW that show the cumulative volume distribution and volume concentration plots for each storm event sample.

Table 8. Particle Size Analysis Results

| Storm # | station | Particle diameters in micrometers[1] $D_{90}$ | $D_{80}$ | $D_{50}$ | $D_{20}$ | $D_{10}$ |
|---|---|---|---|---|---|---|
| 1 | inlet | 140.0 | 85.2 | 31.6 | 11.7 | 5.1 |
| | outlet | 119.0 | 72.2 | 26.7 | 11.7 | 5.1 |
| 2 | inlet | 195.0 | 165.0 | 85.2 | 37.2 | 19.2 |
| | outlet | 195.0 | 165.0 | 85.2 | 37.2 | 19.2 |
| 3 | inlet | 165.0 | 140.0 | 61.2 | 19.2 | 6.0 |
| | outlet | 165.0 | 119.0 | 51.9 | 16.3 | 6.0 |
| 4 | inlet | 140.0 | 72.2 | 26.7 | 11.7 | 5.1 |
| | outlet | 140.0 | 72.2 | 31.6 | 11.7 | 6.0 |
| 5 | inlet | 140.0 | 72.2 | 22.7 | 8.4 | 3.7 |
| | outlet | 140.0 | 72.2 | 31.6 | 11.7 | 5.1 |
| 6 | inlet | 140.0 | 85.2 | 37.2 | 9.9 | 3.7 |
| | outlet | 165.0 | 101.0 | 43.9 | 13.8 | 5.1 |
| 7 | inlet | 140.0 | 72.2 | 26.7 | 9.9 | 4.3 |
| | outlet | 165.0 | 101.0 | 37.2 | 11.7 | 5.1 |
| 8 | inlet | 140.0 | 72.2 | 31.6 | 9.9 | 4.3 |
| | outlet | 140.0 | 72.2 | 31.6 | 9.9 | 3.7 |
| 9 | inlet | 140.0 | 72.2 | 26.7 | 8.4 | 3.7 |
| | outlet | 140.0 | 85.2 | 26.7 | 9.9 | 4.3 |
| 10 | inlet | 140.0 | 72.2 | 26.7 | 8.4 | 3.7 |
| | outlet | 140.0 | 72.2 | 26.7 | 9.9 | 4.3 |
| 11 | inlet | 140.0 | 72.2 | 26.7 | 7.1 | 2.2 |
| | outlet | 140.0 | 72.2 | 26.7 | 8.4 | 2.6 |

[1] Particle size analysis was determined for particles 1.25-212 micrometers.

### 3.4 QA/QC RESULTS

Laboratory quality assurance/quality control (QA/QC) consisted of blanks, duplicates, check samples, and matrix spikes. Results of the laboratory QA/QC can be found within each lab report in Appendix B. Based on the lab reports, all lab QA/QC criteria were met except for: (1) the temperature of most samples submitted and (2) the holding time for metals analysis (24 hours recommended) of samples submitted for storm #1, which were delivered to NCA after approximately 27 hours, and (3) the holding time of samples submitted for storm #2 for PSA (48 hours recommended), which were delivered to UW after 58 hours. Holding times began at the time the last aliquot for each storm event was pumped into the composite. Samples usually did not have time to cool to the preferred temperature of 4ºC after being placed on ice at the field site because the field site was close to the laboratory (an approximate 5-minute drive).

The results of the field QA/QC samples are presented in Table 9. The field blank was collected from the outlet station after storm #3 and the field split was taken from the inlet and outlet samples collected for storm #9 by shaking and pouring off portions from the composites. A field blank was not collected from the inlet station due to oversight. Non-detect (ND) values were reported for all of the field blank parameters, except for a pH value of 5.55 and an ortho-P value of 0.00429 mg/L. Even though ortho-P was reported in the field blank, the actual presence of phosphorus in the field blank was questionable since TP was ND, therefore it was decided not to reanalyze the field blank. In addition, further investigation of ortho-P was deemed unnecessary since ortho-P is not a parameter that Vortechs is designed to remove.

Table 9 also shows the relative percent difference (RPD) values for the field split, which is calculated at the difference between the sample and split values divided by their mean (inlet to inlet and outlet to outlet). The RPD values were within the acceptance criterion in the QAPP of ±20 percent for all parameters except the inlet TSS and TP at the inlet, which were 37.5 percent and –96.5 percent, respectively. Since the RPD values exceeded the criterion for TSS and TP, the field split should have been reanalyzed for TSS and TP but was not due to oversight.

Table 9. Results of Field QA/QC Samples

| | Field Blank[1] | Storm #9 Sample | | Storm #9 Field Split | | Relative Percent Difference (RPD)[2] | |
|---|---|---|---|---|---|---|---|
| **Parameter, units** | **5/15/01** | **inlet** | **outlet** | **inlet** | **outlet** | **inlet** | **outlet** |
| TSS, mg/L | ND | 190 | 150 | 130 | 140 | 37.5% | 6.9% |
| Turbidity, NTU | ND | 53.9 | 56.0 | 58.0 | 45.8 | -7.3% | 20% |
| pH, unitless | 5.55 | 6.89 | 6.99 | 6.95 | 6.95 | -0.9% | 0.6% |
| Hardness, mg eq. $CaCO_3$/L | ND | 31.1 | 26.0 | 26.6 | 26.6 | 15.6% | -2.3% |
| Total Zinc, mg/L | ND | 0.0972 | 0.0766 | 0.0800 | 0.0790 | 19.4% | -3.1% |
| Diss. Zinc, mg/L | ND | 0.0156 | 0.0144 | 0.0176 | 0.0136 | -12% | 5.7% |
| TP, mg/L | ND | 0.06980 | 0.18000 | 0.20000 | 0.19100 | -96.5% | -5.9% |
| Ortho-P, mg/L | 0.00429 | 0.01380 | 0.01120 | 0.01300 | 0.01170 | 6% | -4.4% |

[1] The field blank sample was collected at the outlet.
[2] RPD is calculated as the difference between the sample and the split divided by their average (that is (x-y)/[(x+y)/2]).

## 3.5 MAINTENANCE INSPECTIONS

Results of sediment depths in the upstream manhole, grit chamber of the Vortechs unit, and downstream manhole are presented in Figure 4. Sediment depths ranged from 0 to 24 inches in the upstream manhole, 0 to 44 inches in the grit chamber, and 0 to 7.2 inches in the downstream manhole. The upstream manhole, grit chamber, and downstream manhole were cleaned once during the project on April 17-18, 2000 prior to the beginning of water quality sample collection.

Twenty-two maintenance inspections were performed on the Vortechs unit. Visible sheen was observed 13 times in the grit chamber, 3 times in the upstream manhole, and 4 times in the downstream manhole. Floatables were observed 16 times in the grit chamber, 5 times in the upstream manhole, and 2 times in the downstream manhole. The notes for the maintenance inspections are in Appendix B.

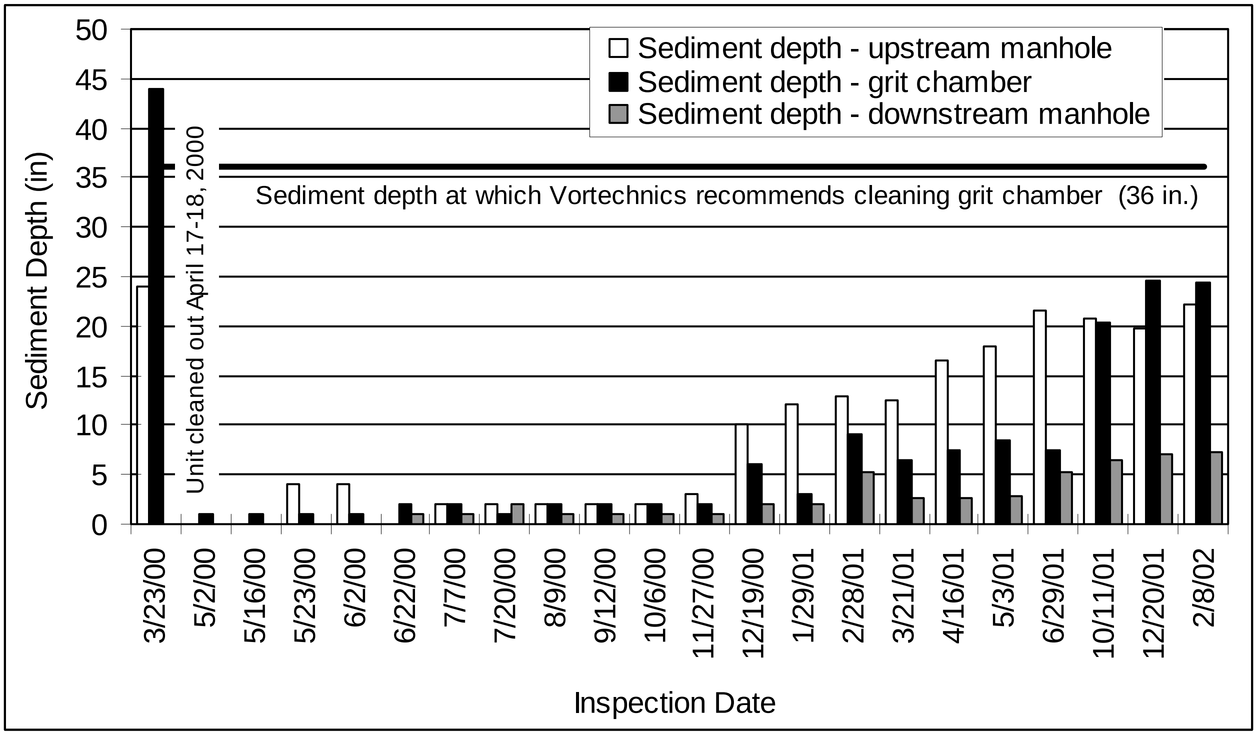


Figure 4. Sediment Depths in Vortechs Unit

## 4.0 DISCUSSION

The scope of work for the SR 405 Project included only limited data analysis, specifically removal efficiency calculations, correlation analyses of removal efficiencies to a few variables, and analysis of maintenance needs of the Vortechs unit studied. Correlations are discussed between storm removal efficiencies (SRE) and three variables: (1) storm event mean flow rate, (2) storm event peak flow rate, and (3) inlet parameter concentration. Correlations are also considered between inlet and outlet concentrations. Maintenance requirements are discussed based on sediment accumulation and hydraulic conditions at the Vortechs installation. Analysis of the effect of other variables on removal efficiencies, especially particle sizes, was not included in the scope of work and is discussed only minimally in this report.

### 4.1 REMOVAL EFFICIENCIES

For each parameter, three plots were created to detect correlations between SRE and storm event mean flow rates, storm event peak flow rates, and inlet event mean concentrations (EMC). A fourth plot was created for each parameter to detect correlation between inlet EMC and outlet EMC for each storm event. For the inlet EMC versus outlet EMC plots, the 0 percent, 25 percent, 50 percent, and 75 percent SRE upper boundaries are shown as dashed lines. Data points on each plot correspond to the storm numbers 1 through 11.

As indicated in the QAPP (Taylor Associates, Inc. 2001), no statistical tests (such as regression) were performed on the data. However, as stipulated in the QAPP, correlation coefficients were calculated for the data plotted in Figures 5 through 28 and are presented in Table 9. All correlation values for mean flow rate versus SREs were negative (except for turbidity) and ranged from –0.54 to 0.44. Correlation values comparing peak flow rates to SREs were all positive (except for dissolved zinc) and ranged from –0.01 to 0.67. Correlation values comparing inlet concentrations to SREs for each parameter were all positive and ranged from 0.29 to 0.72. Correlation values comparing inlet and outlet concentrations for each parameter were all positive and ranged from 0.49 to 0.99.

Table 10. Correlation Coefficients

| | **Correlation Coefficients** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Mean flow rate** | **Peak flow rate** | **TSS inlet** | **Turbidity inlet** | **Total Zn inlet** | **Diss. Zn inlet** | **TP inlet** | **Ortho-P inlet** |
| **SRE, TSS** | -0.07 | 0.27 | 0.41 | - | - | - | - | - |
| **SRE, Turbidity** | 0.44 | 0.67 | - | 0.58 | - | - | - | - |
| **SRE, Total Zn** | -0.52 | 0.03 | - | - | 0.72 | - | - | - |
| **SRE, Diss. Zn** | -0.54 | -0.01 | - | - | - | 0.29 | - | - |
| **SRE, TP** | -0.46 | 0.04 | - | - | - | - | 0.56 | - |
| **SRE, Ortho-P** | -0.13 | 0.17 | - | - | - | - | - | 0.37 |
| **TSS outlet** | - | - | 0.99 | - | - | - | - | - |
| **Turbidity outlet** | - | - | - | 0.93 | - | - | - | - |
| **Total Zn outlet** | - | - | - | - | 0.92 | - | - | - |
| **Diss. Zn outlet** | - | - | - | - | - | 0.49 | - | - |
| **TP outlet** | - | - | - | - | - | - | 0.88 | - |
| **Ortho-P outlet** | - | - | - | - | - | - | - | 0.84 |

SRE = storm removal efficiency (Method 1 from section 2.2), TSS= total suspended solids, Zn = Zinc, TP = Phosphorus, Ortho-P = orthophosphate phosphorus

### 4.1.1 Total Suspended Solids

Figures 5 through 8 are the storm removal efficiency (SRE) plots for total suspended solids (TSS). Figure 5 indicates no relationship between mean flow rate and SRE for TSS (r=-0.07). Figures 6 and 7 indicate a possible positive relationship between SRE versus peak flow rate and SRE versus inlet concentration for TSS. Storms #10 and #11 had negative removal efficiencies and strongly affect the correlation coefficients of 0.27 and 0.41 seen in Figures 6 and 7. Why storms #10 and #11 produced negative removal efficiencies is unclear. The storm event graphs (Appendix A) for these storms do not indicate errors and the storm event characteristics are within the range of other storm events sampled. Figure 8 indicates that inlet and outlet event mean concentrations (EMC) are highly positively correlated (r=0.99).

Aggregate removal efficiencies for TSS were approximately 20 percent. According to Vortechnics, the Vortechs unit is designed to remove up to 80 percent net TSS annually. One possible reason for the lower TSS removals seen in this study is that grain sizes for this project were smaller than typical storm water runoff particle sizes: $D_{90}$ of 212 μm, $D_{80}$ of 150 μm, and $D_{50}$ of 75 μm (Ecology 2001a). The smaller particles in the samples collected for this study may have less of a tendency to drop out of suspension in the grit chamber than larger particles typically associated with stormwater runoff.

### 4.1.2 Turbidity

Figures 9 through 12 are the storm removal efficiency plots for turbidity. Figures 9 through 11 show possible positive relationships between SRE for turbidity and mean flow rate (r=0.44), peak flow rate (r=0.67), and inlet concentration (r=0.58), respectively. The data show much scatter in the low-range of mean flow rates and in the lower range of peak flow rates. Turbidity removal generally increases with increasing inlet turbidity values. The greatest variability of turbidity removal is in the lower range of inlet turbidity (approximately 0-50 NTU). For higher inlet turbidity values between 50 and 300 NTU, removal efficiency increased with a maximum removal of almost 50 percent. Figure 12 indicates a strong positive relationship (r=0.93) between inlet and outlet turbidities.

### 4.1.3 Total Zinc

Figures 13 through 16 are the storm removal efficiency plots for total zinc. With the exception of storm #6, SREs appear to vary around 0 percent removal efficiency for total zinc plus or minus approximately 22 percent. Storm #6 had the lowest inlet concentration of zinc although storm #6 had a negative SRE, the outlet concentration was still lower than for other storm events. Figure 16 shows a strong correlation between the inlet and outlet EMCs for total zinc (r=0.92).

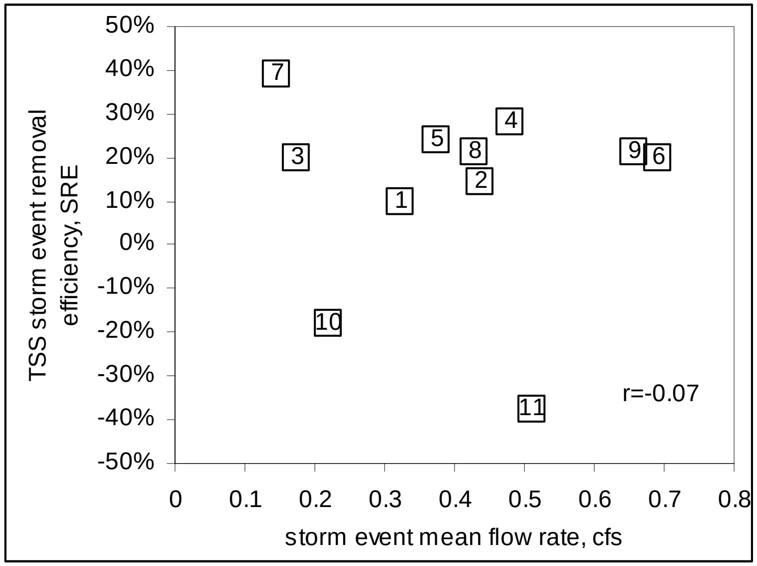


Figure 5. Mean Flow Rate vs. SRE for TSS

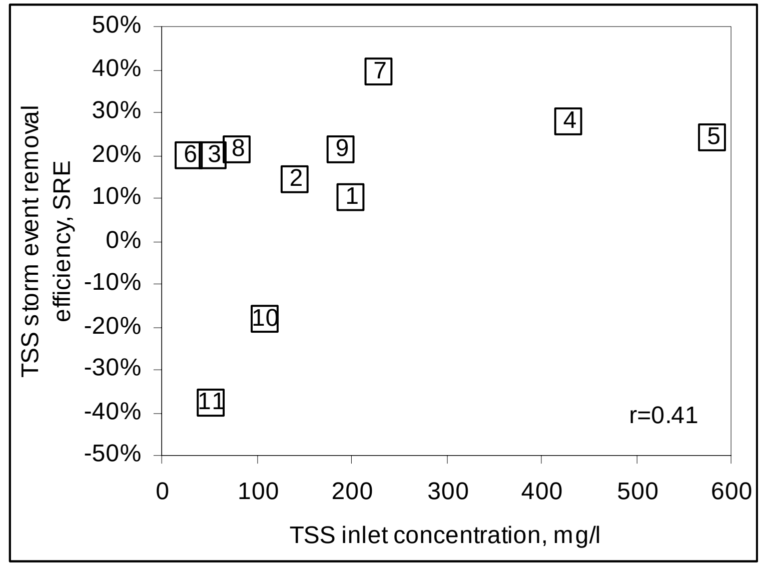


Figure 7. Inlet Concentration vs. SRE for TSS

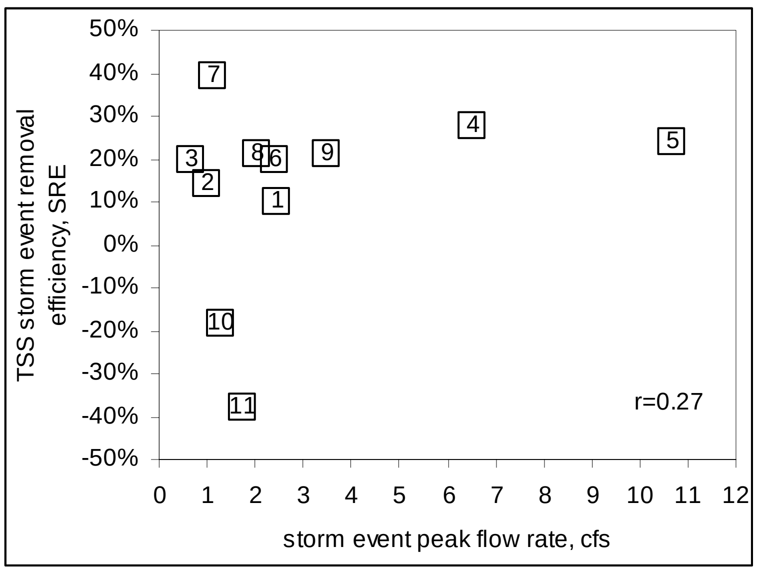


Figure 6. Peak Flow Rate vs. SRE for TSS

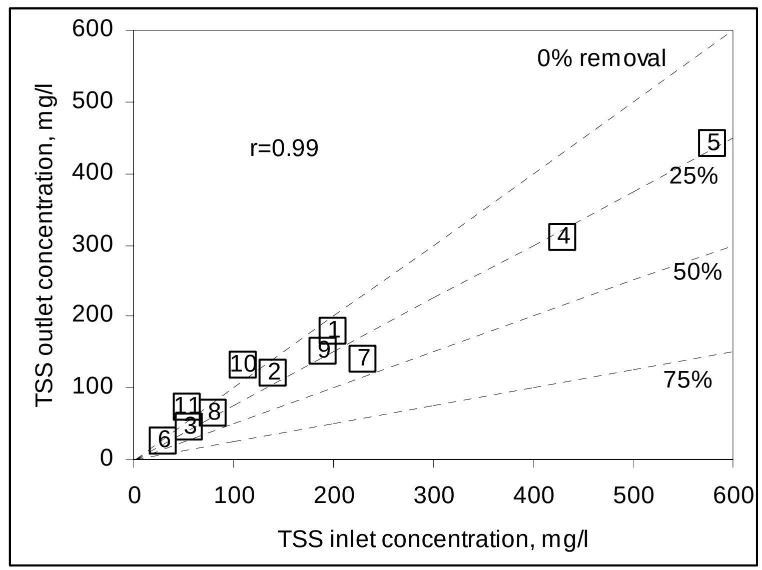


Figure 8. Inlet vs. Outlet Concentration for TSS

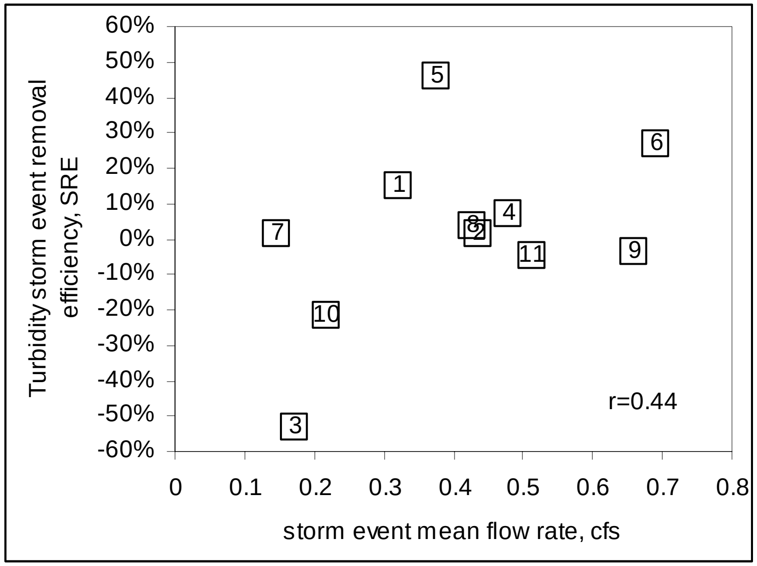

Figure 9. Mean Flow Rate vs. SRE for Turbidity

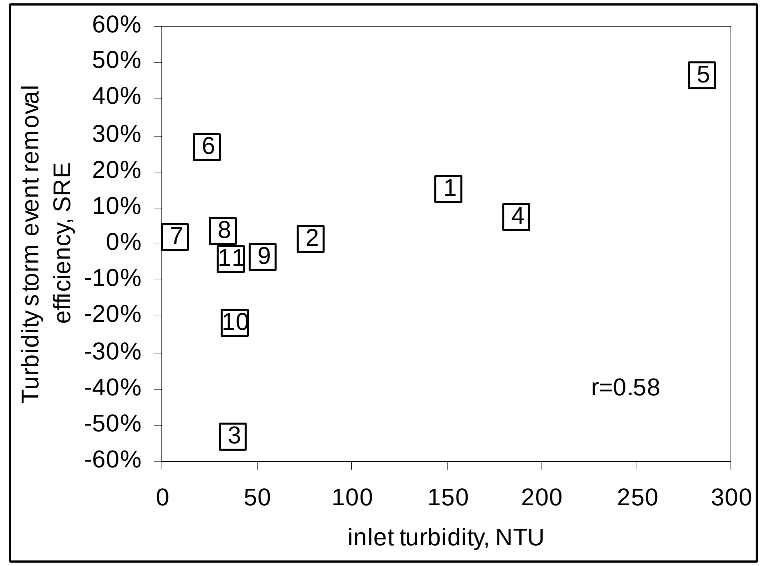

Figure 11. Inlet Turbidity vs. SRE for Turbidity

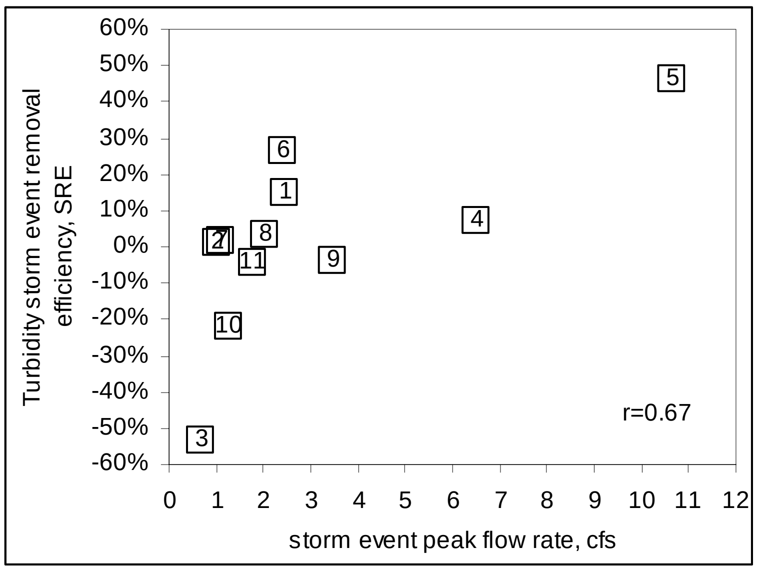

Figure 10. Peak Flow Rate vs. SRE for Turbidity

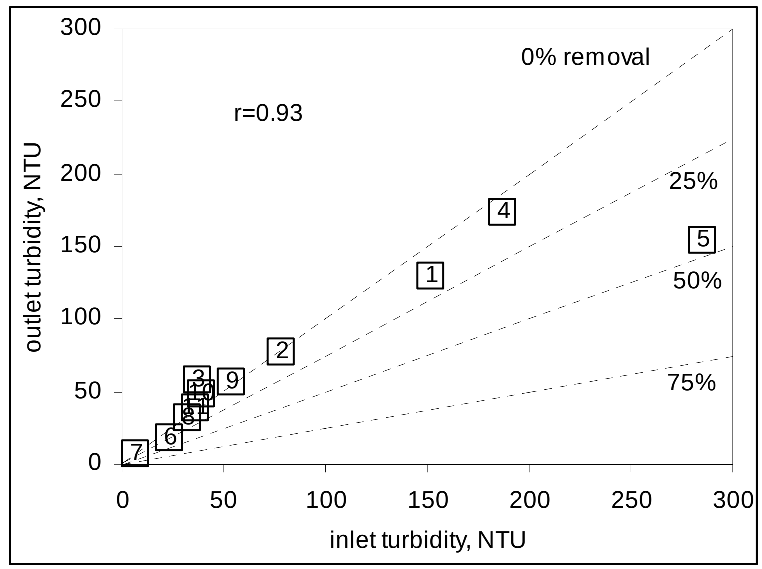

Figure 12. Inlet vs. Outlet Turbidity

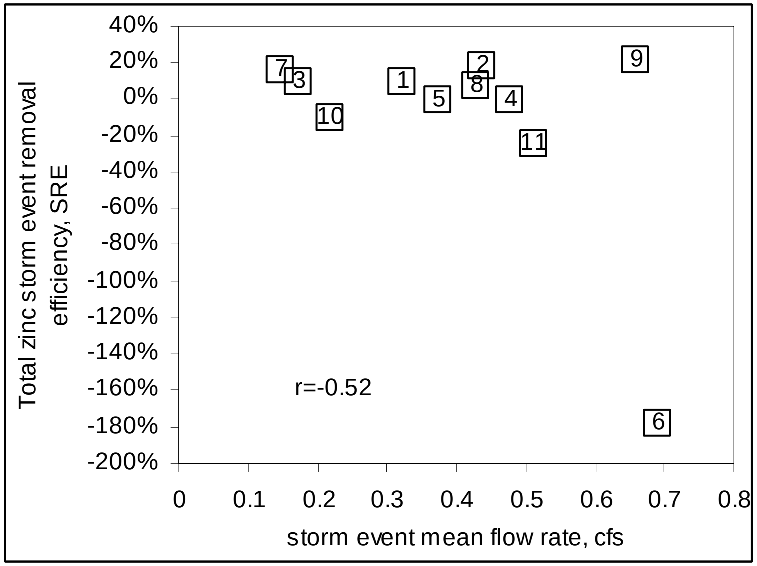


Figure 13. Mean Flow Rate vs. SRE for Total Zinc

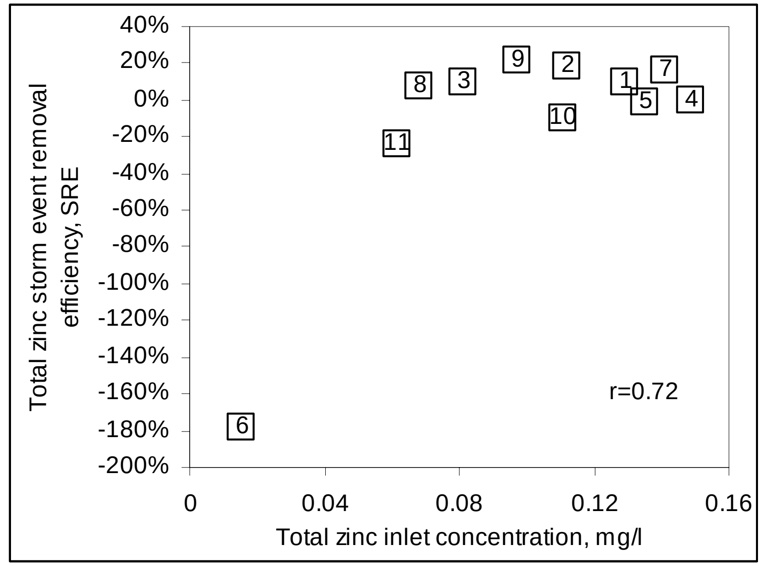


Figure 15. Inlet Concentration vs. SRE for Total Zinc

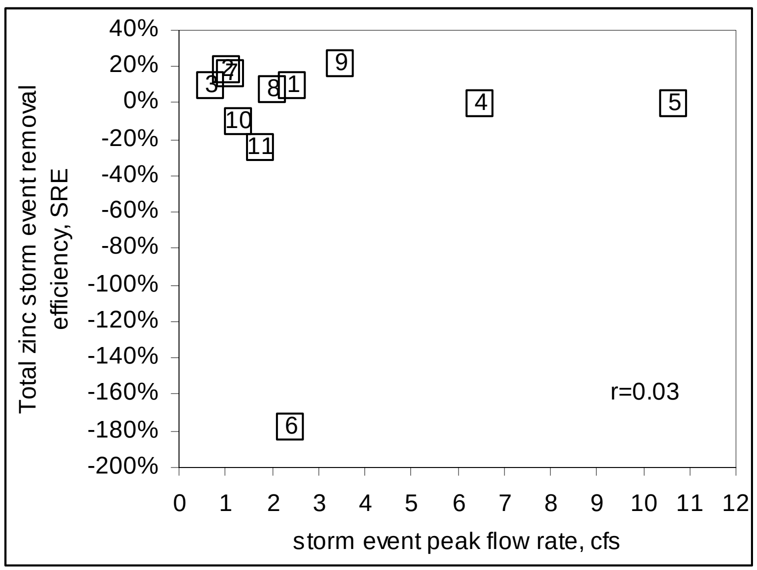


Figure 14. Peak Flow Rate vs. SRE for Total Zinc

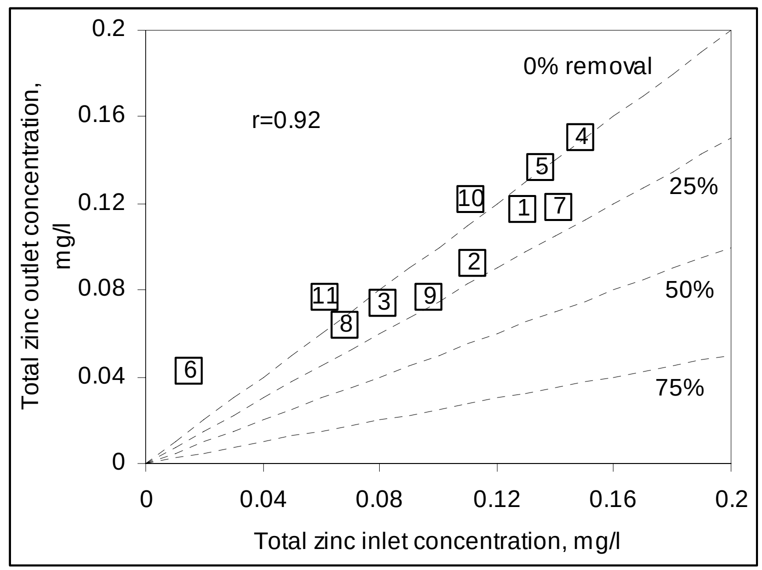


Figure 16. Inlet vs. Outlet Concentration for Total Zinc

### 4.1.4 Dissolved Zinc

Figures 17 through 20 are the storm removal efficiency plots for dissolved zinc. With the exception of storms #6 and #11, SREs tended to vary around 0 percent removal for dissolved zinc plus or minus approximately 40 percent. Storms #6 and #11 appear to be outliers and consequently affect the values of the correlation coefficients shown in Figure 17 through 19. No clear relationships appear to be present between SREs for dissolved zinc and mean flow rate (Figure 17), peak flow rate (Figure 18) and inlet dissolved zinc concentration (Figure 19). Inlet versus outlet dissolved zinc concentrations (Figure 20) appear to be moderately correlated (r=0.49).

### 4.1.5 Total Phosphorus

Figures 21 through 24 are the storm removal efficiency plots for total phosphorus (TP). No clear relationships appear to be present between SREs and mean flow rate (Figure 21) or peak flow rate (Figure 22). SREs do appear to show a moderately positive trend (r=0.56) when compared to inlet TP concentrations (Figure 23), with all SREs below 0 percent associated with inlet concentrations below approximately 0.3 mg/L. The largest SREs (up to 88 percent) occurred at the higher range (>0.4 mg/L) of inlet TP concentrations. Inlet and outlet TP concentrations appear to be well correlated (r=0.88) as shown in Figure 24.

The field split (taken from the composite for storm #9) showed a high relative percent difference value for TP (-96.5 percent). A sensitivity analysis using the TP concentrations from the split instead of the sample to calculate removal efficiencies produced an SRE of positive 5 percent - much higher that the SRE of negative 158 percent calculated from the original sample concentrations. Using the split results also increases the ARE and AREG values by 2 percent to 5 percent, which slightly increases the overall TP removal efficiency. However, this does not appreciably change the relationships of SREs for TP to mean flow rate, peak flow rate, and inlet concentration.

### 4.1.6 Orthophosphate Phosphorus

Figures 25 through 28 are the storm removal efficiency plots for orthophosphate phosphorus (ortho-P). No clear relationship appears to be present between SREs for ortho-P when compared to mean flow rate (r=-0.13, Figure 25) or peak flow rate (r=0.17, Figure 26). A slight positive trend does exist between SRE and inlet ortho-P concentration (Figure 27). Although storm #4 had almost double the inlet concentration of ortho-P compared to the other storm events, the concentrations do appear to be in the same range of removal efficiencies as other storm events (Figure 27). Inlet and outlet ortho-P concentrations are well correlated (Figure 28).

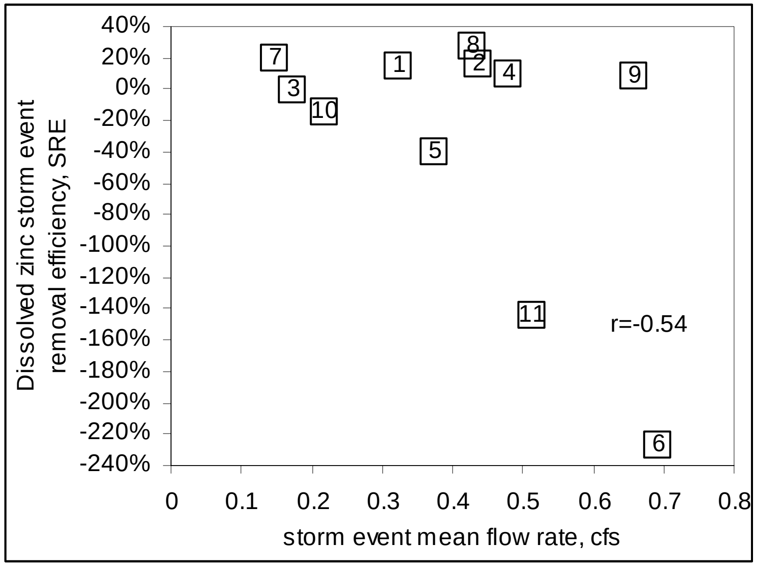


Figure 17. Mean Flow Rate vs. SRE for Dissolved Zinc

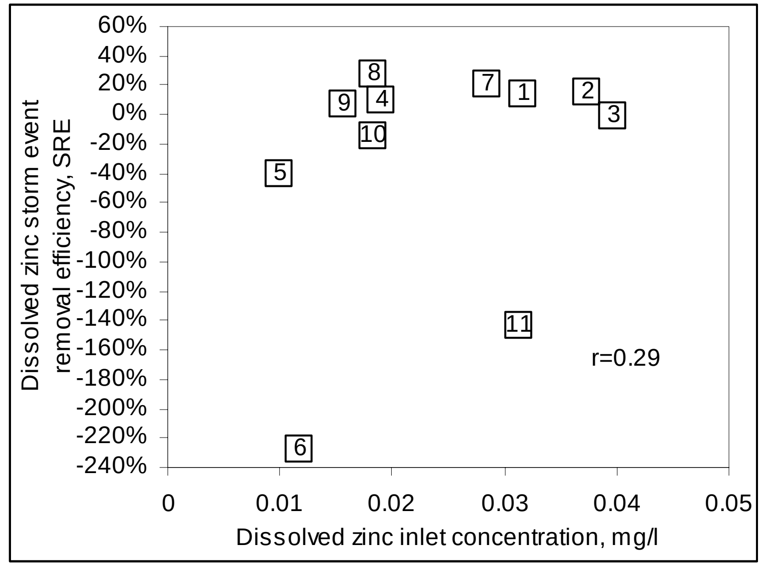


Figure 19. Inlet Concentration vs. SRE for Dissolved Zinc

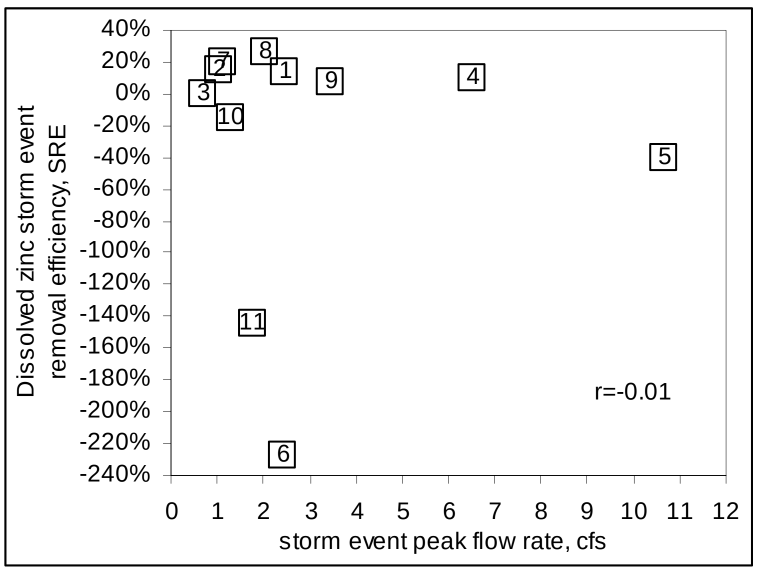


Figure 18. Peak Flow Rate vs. SRE for Dissolved Zinc

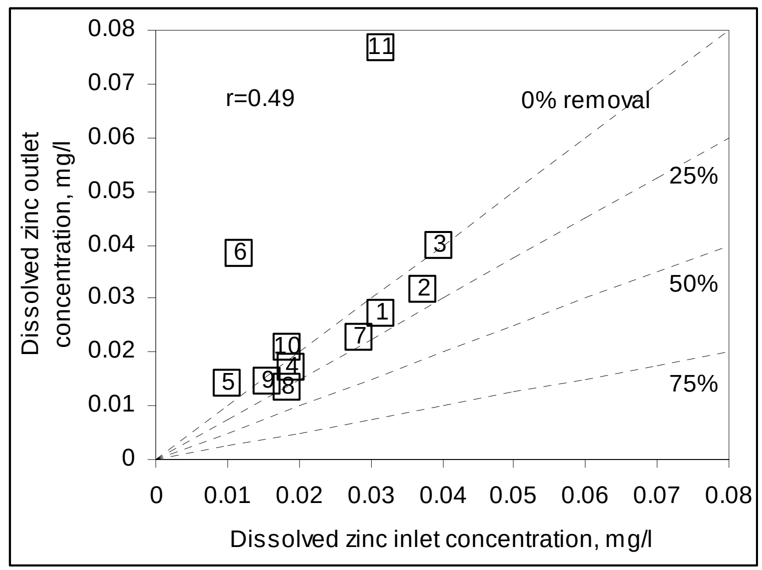


Figure 20. Inlet vs. Outlet Concentration for Dissolved Zinc

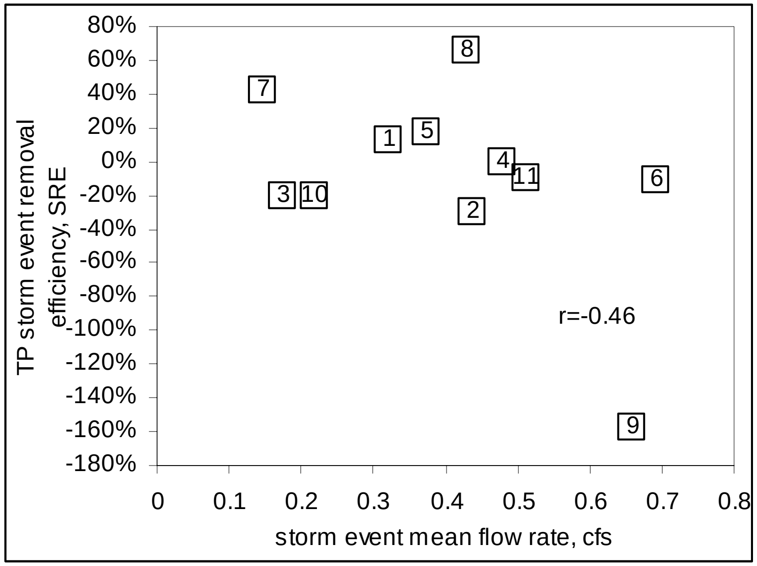


Figure 21. Mean Flow Rate vs. SRE for TP

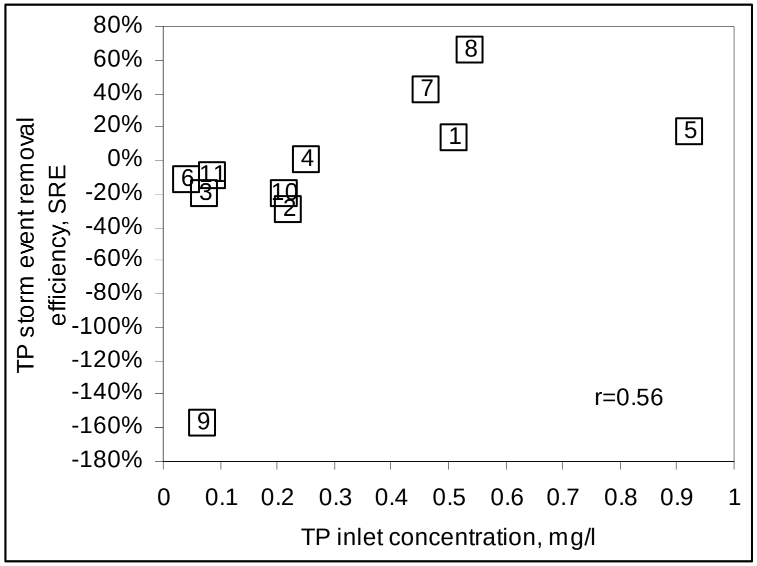


Figure 23. Inlet Concentration vs. SRE for TP

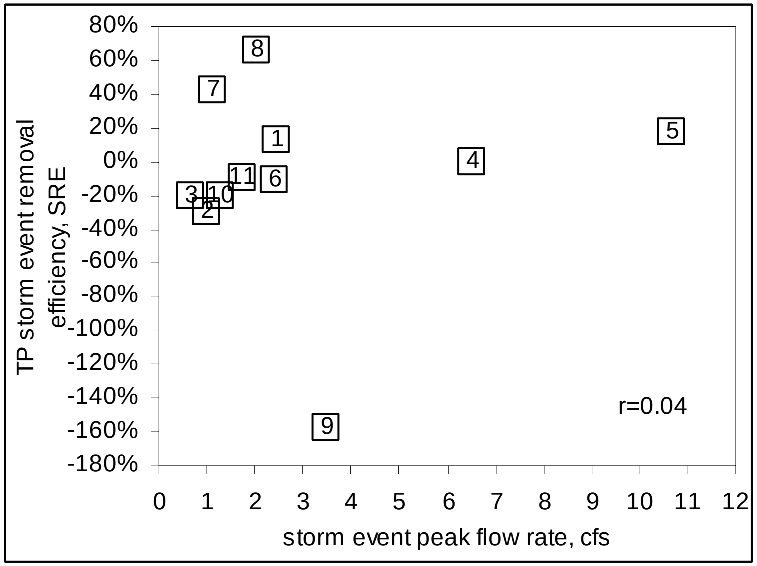


Figure 22. Peak Flow Rate vs. SRE for TP

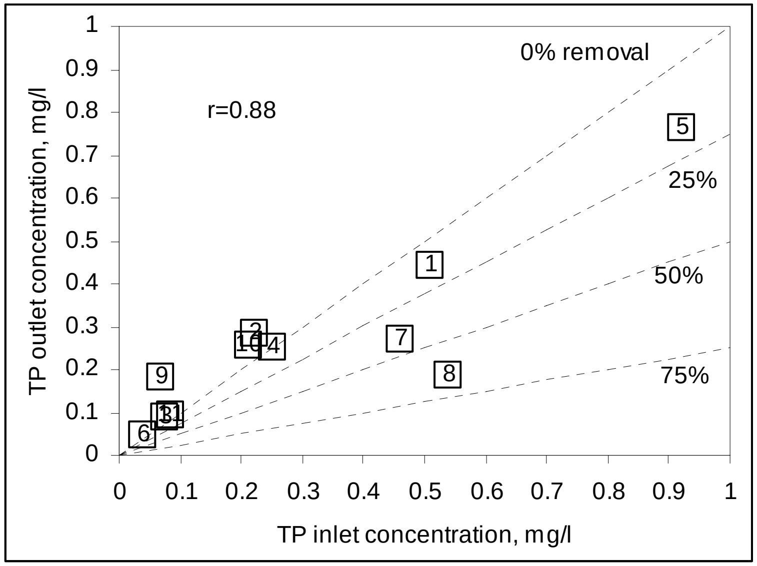


Figure 24. Inlet vs. Outlet Concentration for TP

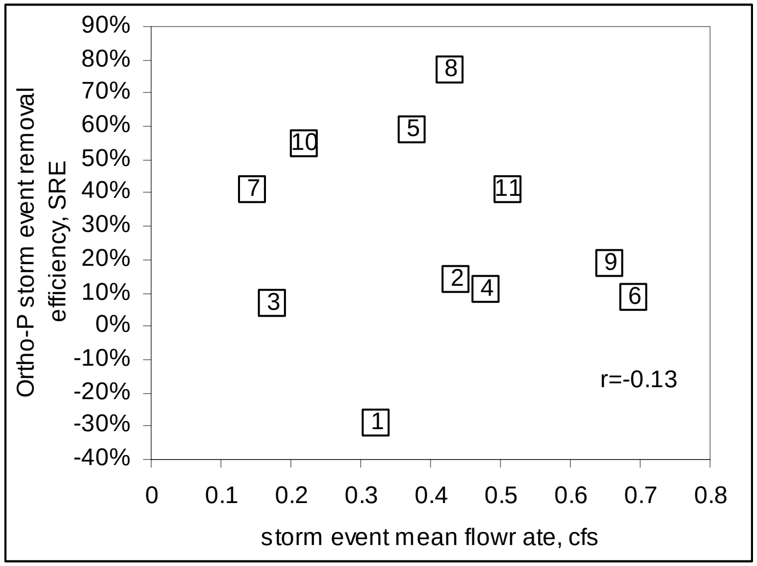


Figure 25. Mean Flow Rate vs. SRE for Ortho-P

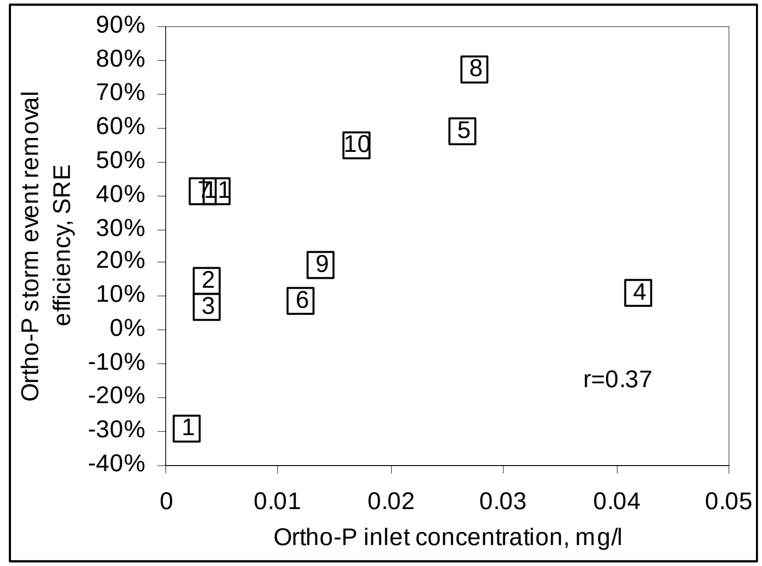


Figure 27. Inlet Concentration vs. SRE for Ortho-P

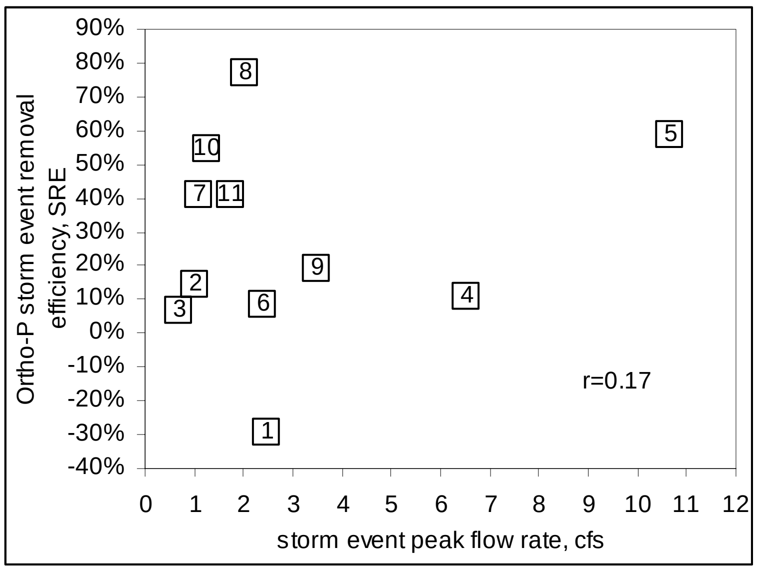


Figure 26. Peak Flow Rate vs. SRE for Ortho-P

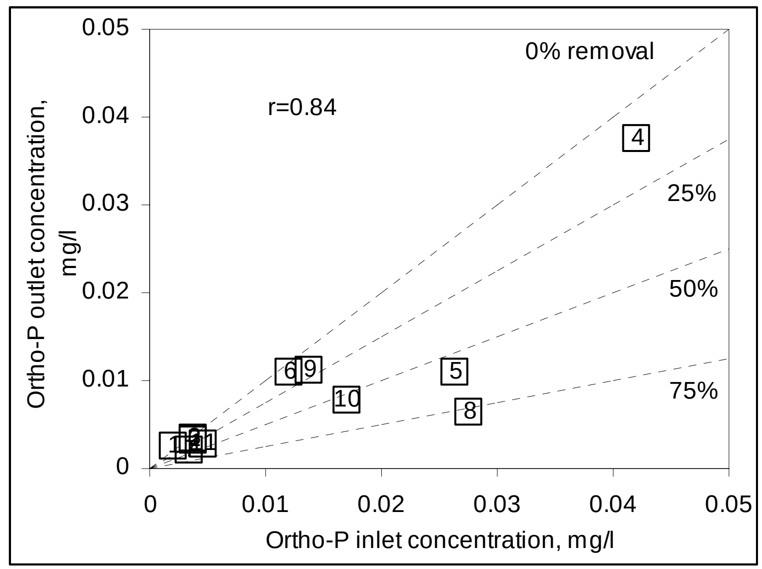


Figure 28. Inlet vs. Outlet Concentration for Ortho-P

## 4.2 OBSERVATIONS ON SAMPLING METHODS

Sand and gravel (up to approximately 75 millimeters in diameter) were noted during many maintenance inspections moving through the inlet pipe into the Vortechs unit as bedload. Bedload was not measured as part of this study, however it is presumed the Vortechs removed bedload since sediment this size was not observed in the outlet pipe. Therefore, the net sediment removal achieved by the Vortechs is likely higher than the TSS removal measured for this study.

During some of the maintenance inspections, an accumulation of fine sediment up to approximately 1 inch deep was observed in the last few feet of the outlet pipe (near the outlet sampler intake line). This deposition of fine sediment may have been related to backwater caused by a downstream hydraulic control during periods of low flow. Approximately two inches of standing water was also present in the outlet pipe during base-flow. Sediment may have accumulated in the outlet pipe at the end of some storm events as velocities decreased due to the backwatering effects of the downstream hydraulic control. Because the outlet pipe was clear of sediment during some maintenance inspections, it is thought this sediment was likely flushed out of the outlet pipe as velocities increased during the next storm event. If this sediment had not been flushed out completely at the onset of sample collection, the sampler intake may have picked up some particles in the first few aliquots of the composite resulting in slightly elevated TSS levels in the outlet sample. It is not known for which samples this may have been an issue.

## 4.3 MAINTENANCE REQUIREMENTS

Sediment accumulation in the grit chamber of the Vortechs unit and in the catch basins upstream and downstream of the unit was minimal during the first 7 months after the unit was cleaned over two days in April 2000 (Figure 4). This minimal accumulation is likely due to the summer dry season that followed the cleaning and also the below normal rainfall that occurred during the Fall of 2000 (WRCC 2002).

Sediment depths in all chambers generally increased from December 2000 through February 2002. During Fall 2001 and Winter 2001-02 sediment accumulation in the grit chamber increased markedly once the upstream manhole was filled with sediment to the level of the invert of the pipe into the Vortechs unit. In February 2002 sediment depth in the grit chamber had reached 24 inches, which is 2/3 of the level at which Vortechnics recommends cleaning the unit (36 inches). Based on the sediment accumulation during this study, the Vortechs unit at the SR 405 Project site requires cleaning approximately every 2 years and requires two days for the cleaning process. The upstream and downstream manholes should also be cleaned at the same time to extend the maintenance cycle of the Vortechs unit.

# 5.0 CONCLUSIONS

The objectives of the SR 405 Project were to: (1) evaluate the removal efficiency of a Vortechs unit, and (2) evaluate the maintenance requirements of the unit.

Eleven storm events were successfully sampled to evaluate the removal efficiency of the Vortechs. In summary, the results indicate:

- For total suspended solids (TSS), the aggregate removal efficiency for all storm events was approximately 20 percent, and the TSS removal efficiencies for each storm event were fairly consistent. Correlation analysis indicated generally positive relationships between (1) storm removal efficiencies and peak flow rate and (2) between storm removal efficiencies and inlet concentrations.

- For turbidity, the aggregate removal efficiency for all storm events was approximately 15 percent. The turbidity removal efficiencies for individual storm events varied moderately.

- For total zinc, the aggregate removal efficiency for all storm events was approximately 2 percent. The total zinc removal efficiencies for individual storm events were fairly consistent.

- For dissolved zinc, the aggregate removal efficiency for all storm events was approximately -35 percent. The dissolved zinc removal efficiencies for individual storm events varied greatly.

- For total phosphorus (TP), the aggregate removal efficiency for the eleven storm events was approximately 15 percent. The TP removal efficiencies for individual storm events varied moderately.

- For orthophosphate phosphorus (ortho-P), the aggregate removal efficiency for all storm events was approximately -35 percent. The ortho-P removal efficiencies for individual storm events varied greatly.

- For all parameters, outlet concentrations were moderately to highly correlated to inlet concentrations.

Based on the TSS removal efficiency results, the Vortechs unit evaluated would be unlikely to meet Washington State Department of Ecology's (Ecology) guidelines for emerging stormwater treatment technologies (Ecology 2001c). Ecology's basic treatment criterion is 80 percent removal of TSS for influent concentrations that are greater than 100 mg/L and less than 200 mg/L. This performance goal assumes the stormwater being treated has a typical particle size distribution of $D_{90}$ of 212 μm, $D_{80}$ of 150 μm, and $D_{50}$ of 75 μm. (Ecology 2001a). Particle sizes measured at the inlet station for this project were consistently smaller than Ecology's typical stormwater runoff particle sizes. The smaller particle sizes were thought to be one of the possible reasons for the TSS removal efficiencies in the low range of 20 percent.

Visual observations of sediment movement through the Vortechs provided additional information of system performance.

- Larger sediment, including sand and gravel, was observed moving through the inlet pipe as bedload into the Vortechs unit.  This coarser material was not observed in the outlet pipe and was presumed to be removed by the Vortechs.  These observations suggest the net total sediment removal by the Vortechs was greater than the measured TSS removal.

- A sporadic accumulation of fine sediment in the outlet pipe near the outlet sampler intake was also noted.  This sediment may have affected the TSS levels in some aliquots of the outlet composite sample.  This effect is thought to be minimal however it is not known for which samples this may have been an issue.

Based on maintenance inspections, the Vortechs unit monitored for this study is providing coarse solids removal and is extending the maintenance cycle of the downstream wet pond.  During the two years the Vortechs unit was monitored, sediment accumulation occurred primarily in the upstream manhole until the sump was full.  Once the upstream manhole sump was full, the rate of sediment accumulation in the grit chamber increased.  Based on results from this study, the Vortechs unit and adjacent upstream and manhole at the SR405 Project site requires sediment removal approximately every two years, perhaps more frequently with normal or greater than normal annual rainfall.

Although the evaluated Vortechs would be unlikely to meet Ecology's basic treatment criteria, it would possibly meet Ecology's criteria for Pretreatment for Treatment Train/Retrofit Applications.  While Ecology has no explicit performance standards for these applications, a lesser performance (than required for basic treatment in stand-alone technologies) may be acceptable (Ecology, 2001c).  Ecology has selected the following guidelines for assessing technologies at less-than-basic treatment levels:

- Provides mostly coarse solids removal and can be specified to improve receiving water aesthetics by removing litter and debris.

- Improves the effectiveness, extends the useful life, or extends the maintenance cycle of a downstream treatment device or infiltration facility.

## 6.0 RECOMMENDATIONS

Based on the removal efficiencies observed during this study, a similarly installed Vortechs unit is not recommended to meet Ecology's basic treatment criteria.  However, a similar Vortechs installation may be an appropriate pretreatment technology where coarse solids removal is desired.

Sediment accumulated from the upstream and downstream manholes and from the Vortechs grit chamber should be analyzed to determine the sediment particle size distribution.  This analysis would provide information on the particle sizes removed by the system, could be used to estimate total sediment loading and removal, and would provide some indication of the effectiveness of the unit as a pre-treatment device for coarse solids removal.  In addition, further analysis of the particle size data collected for this project would be appropriate, such as a correlation analysis between removal efficiencies and particle sizes.

As part of routine maintenance, sediment should be removed from any readily accessible upstream manholes when sediment is removed from the Vortechs grit chamber. This would maximize the duration of the maintenance cycle of the unit.

Data from this study should be combined with other studies to determine the statistical significance of the results. Other appropriate studies would ideally include those being conducted on Vortechs units under the TAPE guidelines (Ecology 2001c) in similar and different installations.

In future studies it is recommended to use an experimental design that includes statistical analysis as budgets permit. The paired t-test would allow a statistical comparison of inlet and outlet samples. Sample size, which is often determined by available budget, is usually the limiting factor for creating a statistically valid experimental design. Data from studies such as this one can be used to perform a power analysis or similar procedure to determine the sample size required for a given level of statistical confidence.

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